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Research Article

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Photobiological safety of LED-based lighting systems – theory and practical hazard assessment

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Abstract: This article gives an insight into the theory and application of photobiological safety assessment. To illustrate several aspects of this topic, the project 'Measurement and assessment of optical radiation sources, relevant to the general population – Risk estimation to the eye, especially blue light hazard and glare' by the German Federal Office for Radiation Protection, where 40 different products were measured and assessed, is used as an exemplary case. Products were chosen which were promoted to have a high output intensity and which are available to the public. Most of the products with incoherent radiation were classified in risk group 2 according to DIN EN 62471:2009 [DIN EN 62471:2009 – 'Photobiologische Sicherheit von Lampen und Lampensystemen']. Only a few of them were labeled correctly or had the right warning notice. Additionally, to the results of this market survey, practical aspects of the hazard measurement and assessment are emphasized.

Keywords: blue light hazard; LED; LED measurement; photobiological safety.

1 Introduction

The assessment of photobiological safety has gained much attention as it is listed under the standards for the CE marking of products via the low voltage directive. This makes it an essential part of product safety and thus a measurement acquires increasing importance. The evaluation is claimed to be a very challenging process and for these reasons we want to share our practical experiences gained in this field.

As semiconductor technology has made huge steps triggered by the wide use of LEDs it has led to increasingly powerful light sources. This results in the positive outcome of having more high-performance lighting products, which were formerly only used by professionals, being available to the general public for a relatively affordable price. The negative consequences are higher potential risks through improper use, lack of risk awareness, incorrect labeling for the end user, which is further increased by poor quality control especially for low-price products. It can be observed that especially in the low-cost area, manufacturers try to bypass reliable but sometimes costly measurements at a risk to the consumers.

This development motivated the German Federal Office for Radiation Protection (BfS) to start a program that initiated the measurement and hazard assessment of 40 products. The requirements were availability for private use via the relevant sales channels offline and online. To gain information about the potential risks, the focus was on those lighting products advertised to have special high performance. Those were found, for example, in journals, published comparative tests or by just having the highest performance on packing information, leading to a presumption of high-risk potential. Another criteria in the sample selection was the manufacturer. The distinction was made between branded articles, private brand big sellers and unnamed products mostly found online. This differentiation ensured mapping the whole price range.

The 40 products consisted of 28 coherent and 12 incoherent articles. For incoherent (all LED) articles the focus was on high power bicycle lights and LED flashlights. At a first glance this reduces the validity to a small range of products, but as the same LEDs as well as the optics are used in all fields of general lighting these results can be directly transferred to other applications.

For the bicycle lights, in total five products were chosen consisting of two advertised as high-power products in bike journals. The next two lights were explicitly advertised to be compliant to the German Road Traffic Licensing Regulations [1], which defines special requirements to

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the light distribution and illuminances in a 10-m distance. The last one from an online platform was described as having a luminous flux of 10 000 lumens, resulting in a price range of those products from €9 up to €200.

In total seven flashlights were selected which were mostly bought online due to the market structure. The most important aspect was a high total luminous flux (‘light output’ according to ANSI FL1 [2]) and a high luminous range (‘beam distance’ according to ANSI FL1 [2]). The selection resulted in a price range from €40 to €200.

1.1 Photobiological safety – theory

All incoherent sources were characterized according to the DIN EN 62471:2009 which is the German version of the EN 62471:2008 which is a slightly modified version of the IEC 62471:2006 [3] which is the normative realization of the CIE S 009:2002 [4] by the International Commission on Illumination (CIE). The devised and agreed modifications were necessary due to contradictions between the IEC 62471:2006 and the European Directive 2006/25/EG. The exposure limits of the IEC standard were changed according to the definitions from the European Directive. A practical approach to the assessment is given in IEC TR 62778:2014 [5].

1.2 Regulatory requirements

The DIN EN 62471 in its most recent version from 2009 gives guidance evaluating the photobiological safety of all electrical incoherent, optical broadband radiation sources and explicitly excludes laser radiation. It supplies standardized methods, exposure limits and classification schemes for the assessment of potential risks.

To evaluate the photobiological safety entirely, the following measured values are needed:

- Maximum spectral irradiance
- Maximum spectral radiance
- Projected size of the radiation source

All measurement values and hazard values shall be acquired at the 200 mm distance. In the case of immobile sources for general lighting purposes the measurement values shall be acquired at a distance where the illuminance is 500 lux. This is a standard illuminance in the working plane for rooms like offices, schools, etc. As the safety aspect is not just relevant to the end-user but also to maintenance workers and others, the 200 mm distance is used in most evaluations. All light sources in this study are mobile, which also leads to the use of the 200 mm measurement distance.

1.3 Hazards

The DIN EN 62471 describes several biological hazards within different ranges of optical wavelengths. These are relevant for outer body parts like skin and the cornea (and lens) as well as the imaging part of the eye behind the cornea potentially causing damage to lens and retina. Thus, the hazards for the outer parts are measured by irradiance and the inner ones by radiance (except small sources which are simplified by irradiance).

As each layer of tissue has its own spectral absorption, the spectral composition differs a lot depending on the penetration depth (Figure 1). Additionally, each biological effect has a specific action spectrum which results in the following tables of hazards (Figure 2).

For outer body parts see (Table 1).

And for inner body parts (Table 2).

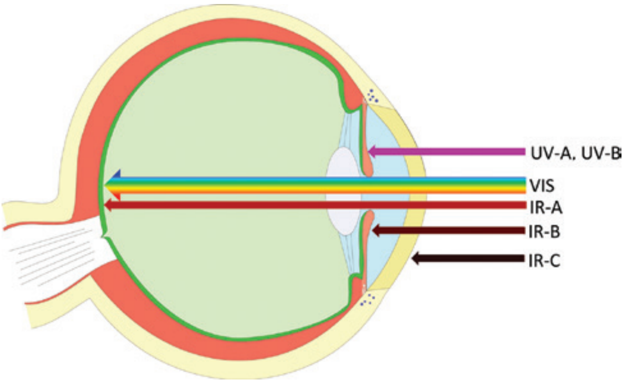


Figure 1: Ocular penetrations depth for each part of the optical spectrum.

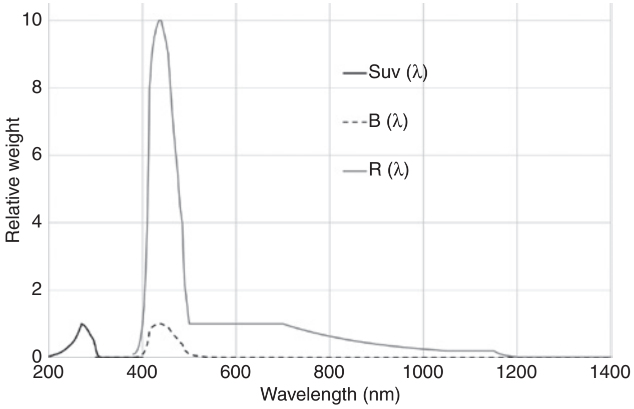


Figure 2: Weighting functions defined in the DIN EN 62471:2009.

Table 1: Hazards to the outer body parts.

Hazard	Symbol	Target tissue	Biological effect	Weighting function	Wavelength range	Exposure limit
UV	E_S	Skin and cornea	Erythema, elastosis and photokeratitis, conjunctivitis, cataracts	$S_{UV}(\lambda)$	200–400	30/t W/m^2
UV-A	E_{UVA}	Lens	Cataracts	–	315–400	10 000/t W/m^2
Infrared	E_{IR}	Cornea	Corneal burn, cataracts	–	780–3000	18 000/t$^{0.75}$ W/m^2
Thermal	E_H	skin	Skin burn	–	380–3000	20 000/t$^{0.75}$ W/m^2

Table 2: Hazards to the inner body parts.

Hazard	Symbol	Target tissue	Biological effect	Weighting function	Wavelength range	Exposure limit
Retinal blue-light	L_B	Retina	Photoretinitis	$B(\lambda)$	300–700	10^6/t W/m^{2}sr
Retinal blue-light – small source	E_B	Retina	Photoretinitis	$B(\lambda)$	300–700	100/t W/m^2
Retinal thermal	L_R	Retina	Retinal burn	$R(\lambda)$	380–1400	50 000/(α t$^{0.25}$) W/m^{2}sr
Retinal thermal – weak visual stimulus	L_{IR}	Retina	Retinal burn	$R(\lambda)$	780–1400	6000/(α) W/m^{2}sr

1.4 Exposure limits

When the eye fixates on an object it is still performing movements with low frequencies at around several hertz. This is needed because of the differential character of the human perception (VERWEIS) and driven by saccades and microsaccades [6]. Looking at this mechanism in the context of potential hazards for the eye means that temporal aspects of the radiation which must also be considered.

The eye movement results in the effect that the image of a light source is blurred over the retinal location proportional to the time the source is fixated. For a duration of 10 s, this means that the eye moves for 0.63° or 11 mrad. At around 100 s, the ability to stare at the target breaks down resulting in a circular region with 5.7° diameter (100 mrad) over which the sources are blurred. For high intensities the exposure of the eye until an avoidance reaction occurs (turning of the head or closing the eyelid) is around 250 ms. During this short period of time, the blur diameter is 1.7 mrad which is around 0.1°.

1.5 Classification

The DIN EN 62471 describes and defines four risk groups used for the classification of lamps and lamp systems. If the exposure limits for a single risk group are exceeded, the device under test (DUT) must be classified into the next risk group. The exposure limits of these groups are based ‘on decades of application experience with lamps and the analysis of unintentional injuries concerning optical radiation’ [6].

The risk groups are:

- Exempt group (RG0) – no photobiological hazard under foreseeable conditions,
- Risk group 1 (RG1) – extremely low risk group; the risk is limited by normal behavioral limitations on exposure,
- Risk group 2 (RG2) – low risk group; the risk is limited by the aversion response to very bright light sources, by heat sensation from sources that primarily emit infrared radiation, or by behavioral limitations for sources primarily emitting ultraviolet radiation. However, this aversion response may be consciously overcome,
- Risk group 3 (RG3) – high risk group; source of optical radiation that may pose a risk of adverse health effects even for momentary or brief exposure.

The basis for those risk groups are permissible exposure times for each hazard and risk group. From these time values and the exposure limits, the emission limits for each risk group can be calculated (Table 3). It the emission

Table 3: Exposure time limits in seconds for continuous sources.

Hazard	RG 0	RG 1	RG 2
UV	30 000 s	10 000 s	1000 s
UV-A	1000 s	300 s	100 s
Infrared	1000 s	100 s	10 s
Blue light	10 000 s	100 s	0.25 s
Retinal thermal	10 s	10 s	0.25 s
Retinal thermal – weak visual stimulus	1000 s	100 s	10 s

limit for RG2 is exceeded for any hazard, the light source is classified as high risk, RG3.

The emission limits in the DIN EN 62471 are given for exposures not longer than an 8-h work day. Any exposure with higher duration is not covered by the standard.

1.6 Measurement of photobiological safety

With all hazards and limits in the standard exactly following human physiology, the ideal measurement would simulate the skin and eye. Within given limits, this is defined in section 1.4 where the measurement is defined inside the normative part of the standard. This is firmly described in the following section before the practical realization is described.

2 Methodology by DIN EN 62471

2.1 Irradiance

By measuring the irradiance, the skin, cornea and lens are simulated. The standard allows for broadband detectors as well as spectral detectors. It defines a cosine angular sensitivity and a detector diameter between 7 mm and 50 mm, where it is important that the diameter is small against the measurement distance. To ensure good results even for inhomogeneous irradiance fields, the minimum diameter is mostly used. For skin hazards, the acceptance angle must be 180°, while for eye hazards it is limited to 80° to mimic the anatomical position of the eyeball.

2.2 Radiance

Following the exposure times for the specific hazards and considering the already described movement of the eye, the standard defines three different viewing fields, to judge each risk group. These are 100 mrad, 11 mrad and 1.7 mrad which must be used to measure the average radiance within this angular field. The DIN EN 62471 describes two ways to realize this (Figures 3 and 4). The first uses an optical system to form an image on the detector. A diaphragm is used to limit the angular averaging of the system. To meet the physiology requirements, the maximum detector area is 7 mm corresponding to the maximum human pupil size.

The alternate method uses a diaphragm in the radiation's exit plane to limit the viewing field. In the standard distance D of 200 mm this leads to diaphragm sizes d of 20 mm, 2.2 mm and 340 µm. The radiance can be calculated using these relations:

$$L=\frac{E}{\Omega}=\frac{E}{\frac{\pi}{4}\gamma^2}=\frac{E}{\frac{\pi}{4}\left(\frac{d}{D}\right)^2}$$

2.3 Measurement value calculation

The final measurement values can be calculated from the spectral measurement data as is shown for the blue light hazard.

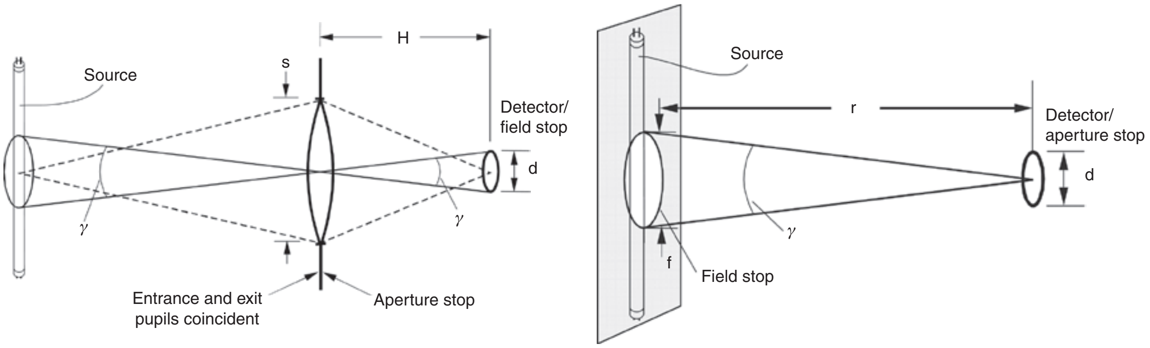
$$L_B=\int_{300}^{700} L_e(\lambda)B(\lambda)d\lambda$$

2.4 Apparent source size

The apparent angular size of the radiation source is needed for calculating the retinal thermal exposure limits. It can be determined using a camera and the full width at half maximum (FWHM) of the luminous area. The spectral sensitivity is relevant here because size can vary for emission wavelengths.

2.5 Spectral measurement specifications

In Appendix B the standard gives advice regarding the spectral measurement equipment. This Appendix is not normative but informative, which means that measurements according to the standard can be conducted even when not following it in detail. In this section a double monochromator is recommended as a measurement device capable of correctly measuring the potential hazards of visible and ultraviolet (UV) radiation.



Figures 3 and 4: Recommended methods for irradiance measurement described in DIN EN 62471.

The sensitivity of the detectors must be high enough to distinguish between noise and a potentially hazardous signal at every wavelength.

2.6 Practical realization

For white LED light sources not all the mentioned hazards are relevant. Because of the spectral composition of LEDs there are just the blue light hazard and retinal thermal hazard which could be caused by LED lighting [7, 8].

The specific realization described here was perfectly suitable for the mentioned project. This is not meant to be the universal best practice for evaluating LEDs, but this project brought some classical challenges to light and as such the method described in the following section performed very well compared to classical methods.

2.7 Spectral measurement device

The spectral irradiance was measured using a specbos 1211 UV from JETI (JETI Technische Instrumente GmbH, Jena, Germany) which was calibrated traceable to NIST standards. It has a spectral range from 230 nm to 1000 nm which is sufficient to judge visible light. The use of a double monochromator – which was used for comparative measurements – would lead to limitations concerning the source stability, as a high-resolution measurement can take several minutes. Of course, the higher straylight (especially in the UV range), spectral bandwidth and dynamic range of an array spectrometer is limited, but most of these disadvantages can be compensated in many situations with knowledge about the measured spectral power distribution (SPD). A scanning double monochromator also often creates problems with modulated sources. The high integration times increase the measurement time by factors.

An often-mentioned disadvantage is the spectral bandwidth of array spectrometers being larger than for scanning monochromators. The general assumption is that the spectral blurring of the energy onto multiple wavelengths causes high uncertainties due to the steep edges of the weighting functions. This is true for the measurement of discharge lamps as can be seen in the following Figures 5 and 6 showing the measurement of a sodium doublet with the specbos 1211 UV and the reference double monochromator. Assuming a weighting function rising from 0 to 1 at 590 nm would cause a misjudgment.

In the practical application of measuring a white LED and multiplying the array spectrometer data as well as the double monochromator data with the $R(\lambda)$ and $B(\lambda)$ function, the result is an overvaluation of 1.0% for $R(\lambda)$ and 0.5% for $B(\lambda)$ which is insignificant compared to other influences.

This shows that the DIN EN 62471 approach to define spectral bandwidths for spectral ranges is not very successful to minimize errors here. A better way would be to define maximum spectral bandwidths for specific weighting functions.

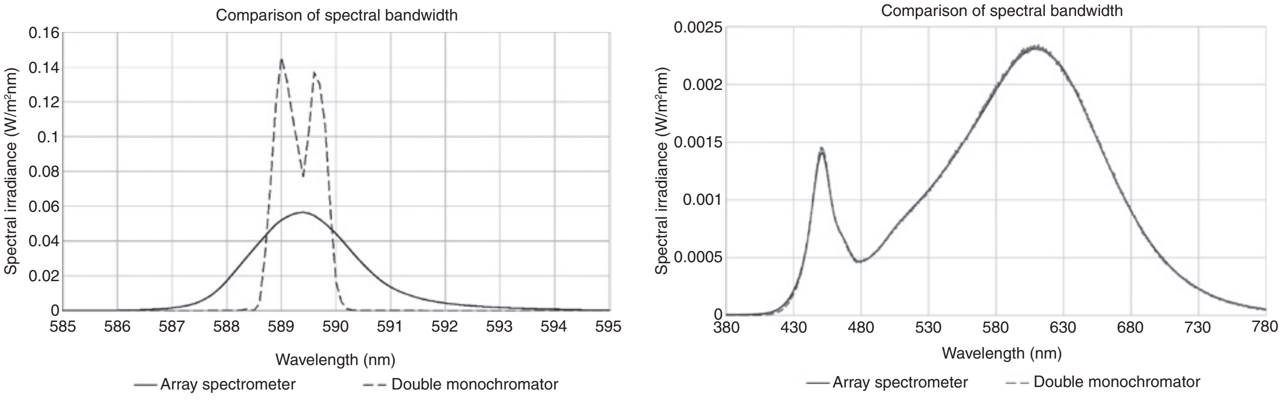
The use of spectral measurement devices is not mandatory. Another technique to realize the specific hazard weighting functions is the use of filters and photodiodes resulting in the required spectral sensitivity. The main argument against this approach is the large (up to 50%) spectral mismatch error in some spectral regions and must be corrected to an acceptable level by using the spectral power distribution. Another point is that the standards are continuously improved, which lead to a different weighting function of $R(\lambda)$ for the most recent publication of EN 62471-5:2015. The already existing parts of the standard will also be adjusted in future, so a laboratory simply must buy new expensive measurement equipment.

2.8 Geometry

The geometry has the biggest influence on measurement uncertainty. To decrease this factor, we decided to use an automotive goniophotometer as a mounting base for the DUTs (Figure 7). This realizes an uncertainty of ±0.1 mm in all axes of the XYZ-table and an uncertainty of ±0.003° for the polar and azimuth axes. Of course, this is not the uncertainty of the absolute positioning, but finding the maximum irradiance and radiances is an iterative process which makes the relative uncertainty the relevant value.

2.9 Irradiance measurements

To realize the apertures with 180° and 80° acceptance angle, the JETI specbos 1211 UV offers a 2π-measurement head and an 80° head limiting the acceptance angle (Figure 8). The maximum irradiance



Figures 5 and 6: Spectral bandwidth comparison of an array spectrometer and a double monochromator.

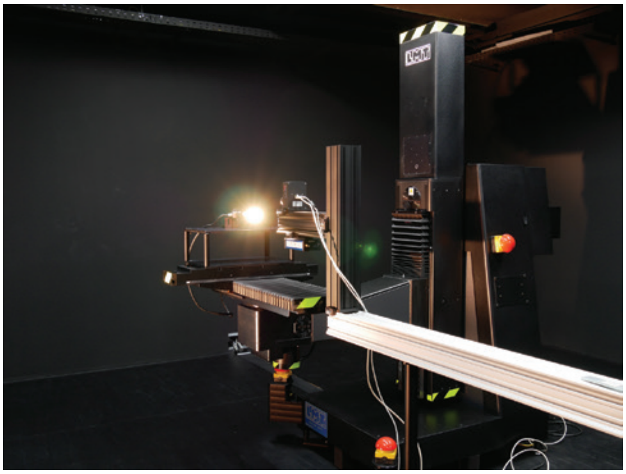


Figure 7: Goniophotometer with video photometer and spectrometer.

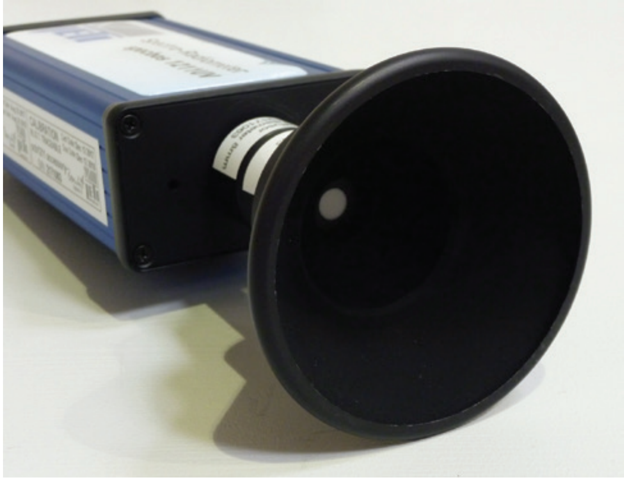


Figure 8: JETI specbos 1211 UV with 80° head.

is determined by scanning a given angular and lateral range which is defined by a preliminary observation of the irradiation pattern to achieve feasible and time-efficient ranges. The goniophotometer automatically measures each position and records the final maximum.

2.10 Radiance measurements

A major challenge in radiance measurement is to know the exact position where the measurement is taken. Using the standard method theoretically gives the opportunity to use the same optical path and exchange the detector by telescope or a camera, but none of the top sellers of measurement equipment is realizing this technique. The most common is the alternative method using no aim and just scanning for the maxima which can take a lot of time for a RG3 scanning with a 340 μm field of view over a luminaire with more than 1 m length. So there has to be an efficient method to solve this.

In this study, the standard method according to DIN EN 62471:2008 for radiance measurement is realized by a luminance and color measuring video photometer LMK 5.1 color by TechnoTeam (TechnoTeam Bildverarbeitung GmbH, Ilmenau, Germany). This spatially resolved measurement system is also used to determine the effective size of the radiation source.

The video photometer consists of a charged-couple device (CCD)-matrix lenses of different focal lengths and with five filters in between with different known spectral transmissions based on the CIE XYZ curves [9]. Measurements with these filters and an unfiltered measurement are used to compute the radiance measurement results. The video photometer is calibrated and traceable photometrically and colorimetrically and the distortion by the optical path of the camera is calibrated using proven methods [10].

Instead of taking circular diaphragms to integrate the mean luminance for each of the three angles (100 mrad, 11 mrad and 1.7 mrad), just a single spatially resolved measurement with all filters is acquired (Figures 9–12). From this measurement image, the maximum luminance for each angle can be computed with image processing by building the filter kernels for the angular size. For some DUTs it came out that the location of the maxima for the apertures are all at different positions. This shows that a measurement exactly following the standard method from DIN EN 62471:2008 takes a vast amount of time for this step. This can be simplified by using the relative SPD and computing the quotient of the respective hazard and the luminance.

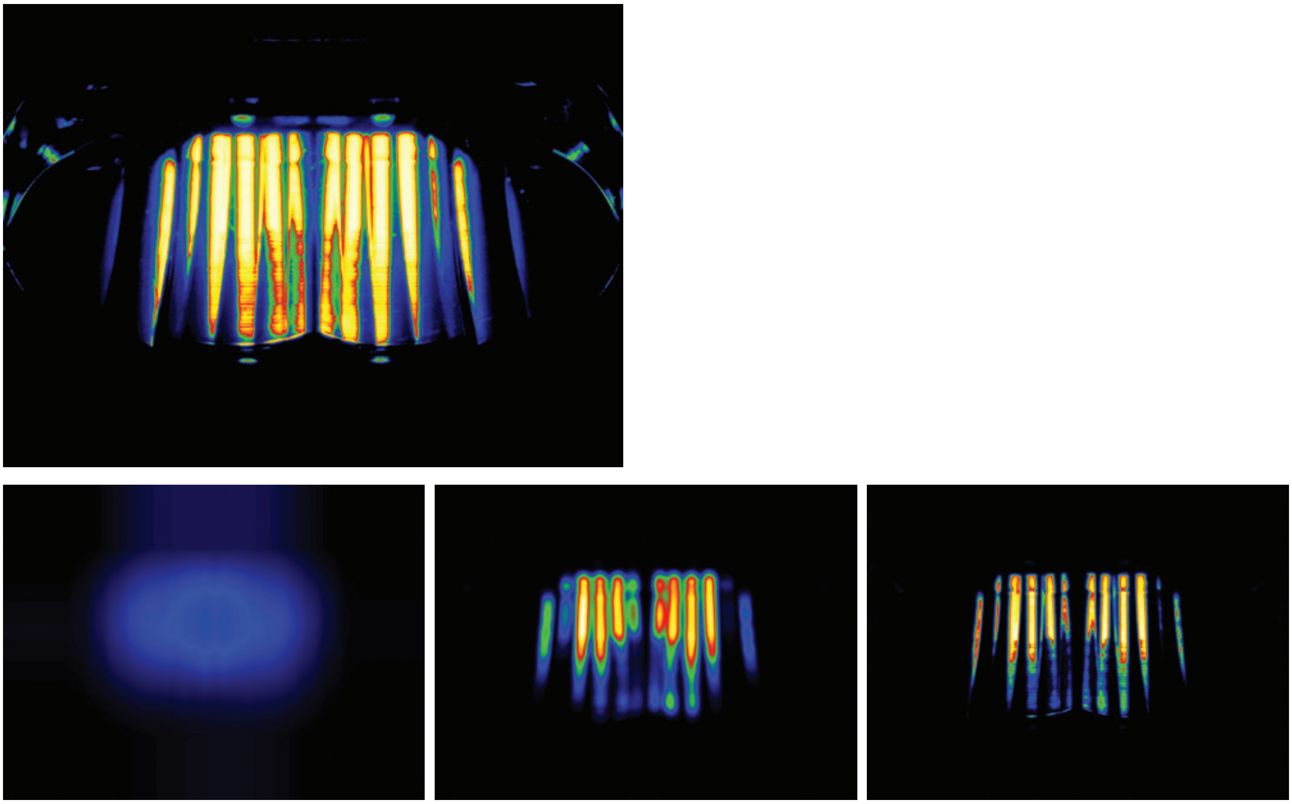
$$K_{B,v} = \frac{\int E_e(\lambda)B(\lambda)d\lambda}{K_m \int E_e(\lambda)V(\lambda)d\lambda}$$

The further computations for hazard assessment are made, by multiplying this factor $K_{B,v}$ with the measured luminances computed for each diaphragm. This is performed for each hazard and diaphragm.

Inhomogeneities in the phosphor coating of the LED chips and variations in the optical path to the exit plane of the lamp system can lead to spectral inhomogeneities. Looking at just one aperture, this additionally leads to different positions of the radiance maximum for each hazard. Following the standard method in this case, a correct maximum search can just be performed using massive simplifications done by qualified laboratory personnel. Using the described method makes this feasible without many compromises because spectral inhomogeneities can be detected. If this is the case, multiple spectral radiances can be measured using the specbos 1211 UV radiance head to model the variance of the SPD and thus variances in $K_{B,v}$ and the other quotients. Afterwards the measurement value for each hazard can be obtained as described above.

2.11 Temporal measurements

The temporal characteristics of the radiation also plays a role in the evaluation. All measurement processes integrating over time, i.e. measuring with a scanning spectrometer, require a temporally stable signal. For LED sources this is the case after the luminaire has reached its thermal equilibrium. To assess the highest potential risk, the DUTs were measured at their highest operation mode, causing the highest thermal load on the casings. As all DUTs are driven by batteries which do not have a constant voltage, there is another factor why the signal is not stable.



Figures 9–12: (last 3 in a row) Computation sequence of 100 mrad, 11 mrad and 1.7 mrad images out of the original measurement.

To get the measurement values at the earliest, most intense and hence most hazardous point, the measurement was conducted in two steps. In the first step, the luminous flux was measured over time, using new batteries using a high-speed measurement system. From this result the point of stable operation can be derived, so all further measurements can then be conducted. The measured values can be scaled back to the very first moment of operation including some spectral uncertainties.

The standard uses special calculations when the radiation is pulse width modulated because this operation interferes with the eye movement. Details on the evaluation of pulse width modulated sources can be found in the DIN EN 62471:2009. To ensure that all DUTs are operated in direct current (DC), a flash measurement system SF105 by LMT was used. This offers irradiance measurements at about 1 million samples per second and showed DC operation for all devices.

2.12 Measurement uncertainty

It has to be mentioned that in general, the limits given in the standard shall not be regarded as defined lines between safe and unsafe levels. Trying to design a product for the extremes, so as not to be classified into a higher risk group is out of the scope of designing safe products for general use, even if safety margins do exist in the standard. In chapter 5.3.3, the DIN EN 62471 requires an analysis of the uncertainties in the normative section. Practically, this is a really hard task and even experienced laboratories are having issues with it [11]. The uncertainty in this publication for an RG3 blue light measurement value is around ±23% ($k=2$) which is huge compared to other measurements. This indicates a need for a discussion on this topic and is the reason why this is not discussed here in more detail.

2.13 Measurement results

The results of the described measurement series are just one indicative example of photobiological hazard assessment and the general variability over different kinds of products is much higher than presented here. Anyway, it is an eye opener to nearly all aspects of evaluating LED products without any claim to be complete.

2.14 Bicycle lights

All the selected bicycle lights within this project are equipped with LEDs and show the typical spectral power distribution. The measured irradiances in the 200 mm distance are shown in Figure 13. All products except the neutral white DUT1.3, use cold white LEDs to gain maximum efficacy. The low-price product DUT1.5 was blue rather than white with a correlated color temperature above 25 000 K (Table 4).

The video photometer measurement was conducted within the first seconds in the brightest, not dimmed mode for the worst-case assessment. The evaluation of the measurements according to DIN EN 62471 showed that just the blue light hazard and the thermal

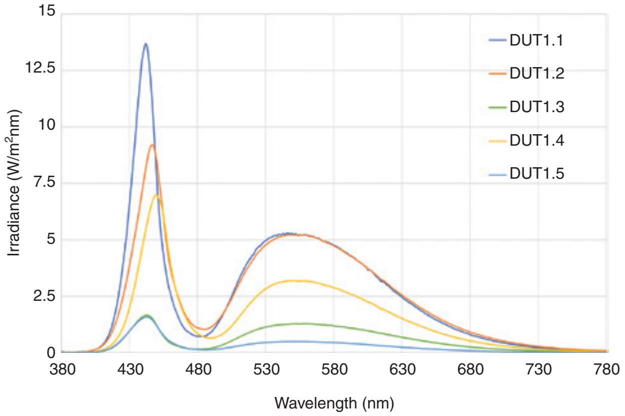


Figure 13: Spectral irradiance of the bicycle lights in 200 mm distance.

Table 4: Measurement results of the tested bicycle lights.

DUT	Light source	Luminous flux			CCT
		Given	Instant	30 min	
DUT1.1	LED	2000 lm	2060 lm	827 lm	6955 K
DUT1.2	LED	1600 lm	1612 lm	803 lm	7467 K
DUT1.3	LED	-	276 lm	262 lm	4916 K
DUT1.4	LED	-	404 lm	320 lm	6389 K
DUT1.5	LED	10 000 lm	177 lm	160 lm	(26 728 K)

retinal hazard are relevant for LED sources. The following table summarizes the measurement values and the respective exposure limits (Tables 5 and 6).

Except for the DUT1.5 which was classified in RG1 with low risk, all other products range in RG2. This is due to exceeding the exposure limits of blue light hazard as well as retinal thermal hazard except for the lower CCT DUT1.3. The significantly lower short wavelength radiation leads to low risk (RG 1) concerning the retinal thermal hazard. For the two high power products from DUT1.1 and DUT1.2, the exposure limits for RG1 are exceed even for the thermal equilibrium after about 10 min.

No bicycle light has a safety notice on the product itself and just DUT1.1 and DUT1.2 put one in the operation instructions.

2.15 Flash lights

The measured spectral irradiances of the flash lights within the project are shown in Figure 14. They are all cold white except for the DUT2.6 at 11 000 K CCT.

The flashlights were also measured and assessed according to ANSI FL1-2009. The relevant results are summed up in Table 7.

The DUT2.3 and the DUT2.7 missed the performance stated in the packing information which was 2000 lm and 10000 lm, respectively. The hazard assessment also exposed the blue light hazard and the thermal retinal hazard to be the only relevant potential risks to the user. The two succeeding tables sum up those results (Tables 8 and 9).

All flashlights shall be classified in RG2 as the exposure limits for RG1 are exceeded for the blue light hazard as well as – except in one case – for retinal thermal hazard. It is important to note that the thermal effect is dominating over the blue light hazard for exposures under 10 s. Even in the stabilized state after half an hour, three of the products still surpass the exposure limits for RG1 for blue light hazard. Only the product DUT2.1 had a safety label on it, drawing attention on potential risks for the eye. All products had a warning in their operating instructions, but according to DIN EN 62471 supplement 1, a clear labeling of the product would be appropriate.

Table 5: Blue light hazard assessment of the bicycle lights.

DUT	Weighting function	Unit	Exposure limits			Measurement value	Max. exposure in s
			RG 0	RG 1	RG 2		
DUT1.1	$B(\lambda)$	W/m²sr	100	10 000	4 000 000	33 700	29.7
DUT1.2	$B(\lambda)$	W/m²sr	100	10 000	4 000 000	33 200	30.1
DUT1.3	$B(\lambda)$	W/m²sr	100	10 000	4 000 000	14 230	70.3
DUT1.4	$B(\lambda)$	W/m²sr	100	10 000	4 000 000	71 700	13.95
DUT1.5	$B(\lambda)$	W/m²sr	100	10 000	4 000 000	8000	12.5

Table 6: Thermal hazard assessment of the bicycle lights.

DUT	Weighting function	Unit	Exposure limits			Measurement value	Max. exposure in s
			RG 0	RG 1	RG 2		
DUT1.1	$R(\lambda)$	W/m²sr	280 000	280 000	710 000	395 000	2.572
DUT1.2	$R(\lambda)$	W/m²sr	280 000	280 000	710 000	405 000	2.324
DUT1.3	$R(\lambda)$	W/m²sr	280 000	280 000	710 000	138 600	169.5
DUT1.4	$R(\lambda)$	W/m²sr	368 421	368 421	934 211	846 000	0.356
DUT1.5	$R(\lambda)$	W/m²sr	280 000	280 000	710 000	89 400	979

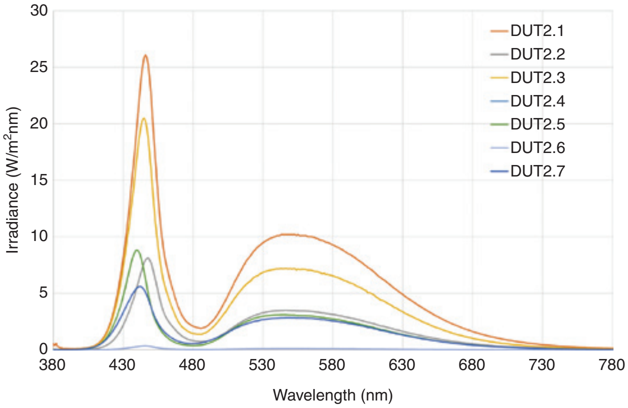


Figure 14: Spectral irradiance of the flash lights in 200 mm distance.

Table 7: Measurement result of the ANSI FL1 parameters.

DUT	Beam distance	Max. luminous intensity	Luminous flux	CCT
DUT2.1	293 m	21 578 cd	639 lm	7271 K
DUT2.2	163 m	6674 cd	966 lm	7022 K
DUT2.3	90.5 m	2046 cd	1394 lm	8134 K
DUT2.4	166 m	472 cd	6921 lm	754 2K
DUT2.5	339 m	28 723 cd	589 lm	6418 K
DUT2.6	242 m	14 660 cd	218 lm	11 371 K
DUT2.7	1658m	687 616 cd	1960 lm	6550 K

3 Conclusion

This exemplary project was chosen because it shows a lot of product variations which can be found in all general lighting products. There is the use of different light guidance technologies, different light sources are used from mid-power to high-power which all together enables generalizing the findings. The measurement results from this project exactly match the general measurement results from 5 years of evaluating visible LED lighting products. The most ‘hazardous’ products with the intended use in lighting, are classified in RG2. To repeat the standard this means ‘low risk’ leading to aversion reactions whenever the level of radiation reaches a potentially hazardous intensity. Until the visual task does not limit avoiding reactions or requires to ‘consciously overcome’ the natural urge to avert from the source, the eye will not be harmed.

Taking white LEDs, to exceed a blue light hazard classification of RG3, the exposure limit of 4 MW/m^{2}sr $B(\lambda)$-weighted radiance must be reached. With a $K_{B,v}$ of a cold white LED of around 0.008 W/lm, this means a chip level luminance maximum of 500 Mcd/m^2. Concerning the retinal thermal hazard from a large source of 100 mrad apparent size, 710 kW/m^{2}sr of $R(\lambda)$-weighted radiance, the luminance must be higher than 1.5 Gcd/m^2 (typical $K_{R,v}$ of 0.00045 W/lm) which currently can be technically realized only by discharge lamps or lasers.

Table 8: Blue light hazard assessment of the flash lights.

DUT	Weighting function	Unit	Exposure limits			Measurement value	Max. exposure in s
DUT2.1	$B(\lambda)$	W/m^{2}sr	100	10 000	4 000 000	45 600	21.93
DUT2.2	$B(\lambda)$	W/m^{2}sr	100	10 000	4 000 000	41 300	24.19
DUT2.3	$B(\lambda)$	W/m^{2}sr	100	10 000	4 000 000	44 100	22.66
DUT2.4	$B(\lambda)$	W/m^{2}sr	100	10 000	4 000 000	26 940	37.1
DUT2.5	$B(\lambda)$	W/m^{2}sr	100	10 000	4 000 000	25 400	39.4
DUT2.6	$B(\lambda)$	W/m^{2}sr	100	10 000	4 000 000	30 100	33.2
DUT2.7	$B(\lambda)$	W/m^{2}sr	100	10 000	4 000 000	142 500	7.02

Table 9: Thermal hazard assessment of the flash lights.

DUT	Weighting function	Unit	Exposure limits			Measurement value	Max. exposure in s
DUT2.1	$R(\lambda)$	W/m^{2}sr	280 000	280 000	710 000	537 000	0.753
DUT2.2	$R(\lambda)$	W/m^{2}sr	318 182	318 182	806 818	492 000	1.779
DUT2.3	$R(\lambda)$	W/m^{2}sr	318 182	318 182	806 818	511 000	1.526
DUT2.4	$R(\lambda)$	W/m^{2}sr	280 000	280 000	710 000	312 000	6.58
DUT2.5	$R(\lambda)$	W/m^{2}sr	28 0000	280 000	710 000	310 000	6.78
DUT2.6	$R(\lambda)$	W/m^{2}sr	368 421	36 8421	534 210	298 000	24.37
DUT2.7	$R(\lambda)$	W/m^{2}sr	2 545 455	2 545 455	6 454 545	1 375 000	104.1

There is one point where indoor lighting differentiates a bit from the presented products, which is the color temperature. In indoor lighting applications the use of lower CCTs is much more common leading to a smaller $K_{B,v}$ which makes the products even less hazardous.

Even though there is no primary risk by exceeding given limits and directly causing physiological damage, it must be emphasized that this does not mean that they are totally free of risks. Especially outdoor products designated to be used in low light conditions, have a great potential of causing glare. The observed glare intensities can lead to several seconds of impaired vision and significantly limits the affected person to detect obstacles, etc. If not used properly, the secondary risk of those high intensity lighting products still exists.

Another point the authors want to emphasize is the importance of measurements in photobiological risk assessment. Of course, the methods applied in this paper are neither brand new nor revolutionary high-tech. They are the application of standards and rules in this field. Nevertheless, even in recent articles on potential photobiological risks of LED lighting [12, 13], these rules are often not correctly applied leading to a lack of measurement information and making reliable comparisons of studies practically impossible. We want to encourage scientists from any field to apply commonly used methods to assess and describe the used radiation sources itself as well as the test geometries to ensure and improve comparability on this sensitive field of research.

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