"Theory and Practical Measurement Results of Modulated Light"

Dipl.-Ing. (DH) Peter Erwin, Director and Design Engineer, Der Lichtpeter, Wöschbacher Str. 26, 75045 Walzbachtal, Germany

Abstract

With a filament as an artificial electric light operated on DC Edison at his time thought to come as close as possible to constant sunlight. Since the existence of the alternating voltage, later in conjunction with fluorescent tubes and now with SSL and other light sources e.g. displays, the light influencing on us consists of a mixture of a direct component and an alternating component. The AC varies arbitrarily in its amplitude, fundamental frequency and waveform. Solely the control of the light emitting element is responsible. It is certain that the AC component has a negative effect on the nervous system of humans and other beings. A currently massively occurring case of light modulation is the "light flicker" of electrically powered illuminants.

Up to now there have been no satisfactory methods to measure light modulation with regard to the compatibility with humans, from which then the quality of a light-emitting object would be derived. The various existing methods for specific application to illuminants have disadvantages, which makes them not marketable.

With the CFD (Compact Flicker Degree) Der Lichtpeter has developed the first light modulation measurement method that meets all requirements to specify standard limits in order to protect the people.

1. Introduction

It is considered ideal to design light sources without modulation. In addition to the cost issue for implementing so, there are also useful properties that contradict this ideal approach. Examples are screens (TV, computer) or optical data transmission via the LED lighting as an alternative to WLAN.
In any case, the electrical control is responsible for the degree of modulation and frequencies. For illuminants, the influence of the AC line voltage and its modification by dimming and pulse width modulation or optical data transmission is crucial.
It is important to set limits in order to protect the people against negative influences. For this purpose a suitable measurement process is required, which is universally applicable to all of the light sources to allow a quantitative comparison.

A universal method for measuring modulated light comprises the following features:

- AC amplitude relative to the direct component of the light (modulation)
- Fundamental frequency of the modulation
- Waveform (all frequency components)
- Contrast (darkest to brightest value)
- Frequency-dependent human perception threshold (consciously / unconsciously)
- Phantom array effect

The measurement process is suitable for the market as soon as the quantification result is a simple measure that allows categorization into quality levels and setting standard limits.

This paper presents the CFD as a suitable measurement method, and proves the CFD to be universal in comparison to other methods by means of different types of modulated light sources:

- Incandescent bulb on mains power supply
- Computer monitor
- TV screen non-interlaced / interlaced (the example of a white screen)
- Fluorescent tube with conventional magnetic ballast on mains power supply
- Fluorescent tube with electronic ballast on mains power supply
- LED illuminant with moderate electronic ballast on mains power supply
- LED illuminant with insufficient electronic ballast on mains power supply
- LED illuminant with insufficient electronic ballast controlled via leading edge dimmer
- LED quasi without electronic ballast controlled via PWM dimmer at 655 Hz

In practice, Der Lichtpeter has surveyed more than 600 light sources and checked the CFD results of extraordinary light emissions visually for plausibility. This confirms the usefulness which is why Der Lichtpeter has developed an all-in-one measuring system. For the benefit of all, Der Lichtpeter has set up a service to have illuminants and other light sources measured regarding their light modulation.

2. Measurement

Basically for all measurement methods, the optical light signal needs to be converted into an electrical voltage signal as lossless as possible. The hardware is preferably to be designed as:

- Using a V-lambda photodiode to suppress the non-visible infrared light component e.g. from an incandescent light bulb.
- Transimpedance amplifier with variable transimpedance for optimal utilisation of the vertical measurement range.
- Anti-aliasing low-pass filters to meet the sampling theorem, depending on the sampling frequency.
- Analog-to-digital converter with a sampling frequency of between 2 kHz and 500 kHz to ensure adequate representation and computation.
- Depending on the calculation method, an acquisition of at least five periods of up to one second duration.

The corresponding captured and digitized measurement signal is subjected to a calculation where the two approaches 'time-based' and 'frequency-based' can be taken as a basis.

2.1. Time-domain calculation methods

Time-based calculation methods are generally not suitable for a universal measure, because the calculated value mainly arises from amplitude ratios. The requirement for a frequency-dependent weighting can therefore not be met.
These include:

- The contrast methods (min−max; RMS) of the companies Admesy B.V.[1] and CHROMA ATE INC[2].
- The becoming popular measuring method according to IES: RP-16-10[3]. Additionally instead of one value this provides the two values %Flicker (modulation) and flicker index, which only together lead to a qualitative assessment, the way, however, is not defined.

2.2. Frequency-domain calculation methods, CFD

For the calculation the measurement signal is decomposed e.g. by Fourier transform into its frequency components. Periodic signals can thus be described as a discrete spectrum of individual frequency components. The modulation fundamental frequency, further frequency components and thus the waveform are considered in the calculation for non-sinusoidal shapes.
The key differences in these processes are the inclusion of frequencies and the **frequency-dependent weighting**. In all procedures listed below the top frequency is set too low to account for the main problem of the light flicker at twice the mains frequency and the phantom array effect:

- For the JEITA method, the companies Admesy B.V.[1] and CHROMA ATE INC[2] apply a frequency-dependent weighting curve to the frequency components, which weights all frequencies ≥ 65 Hz with zero.
- The group ASSIST of the Lighting Research Center[4] weights the frequencies of the signal (sampled with 2 kHz only) on the basis of a characteristic inspired by the flicker fusion threshold of 70 Hz.
- Also the weighting in the dissertation by M.Sc. Farhang Ghasemi Afshar (2009) [5], which reflects the studies by Kelly (1961) and Henger (1986), is modelled on the flicker fusion threshold at about 70 Hz.

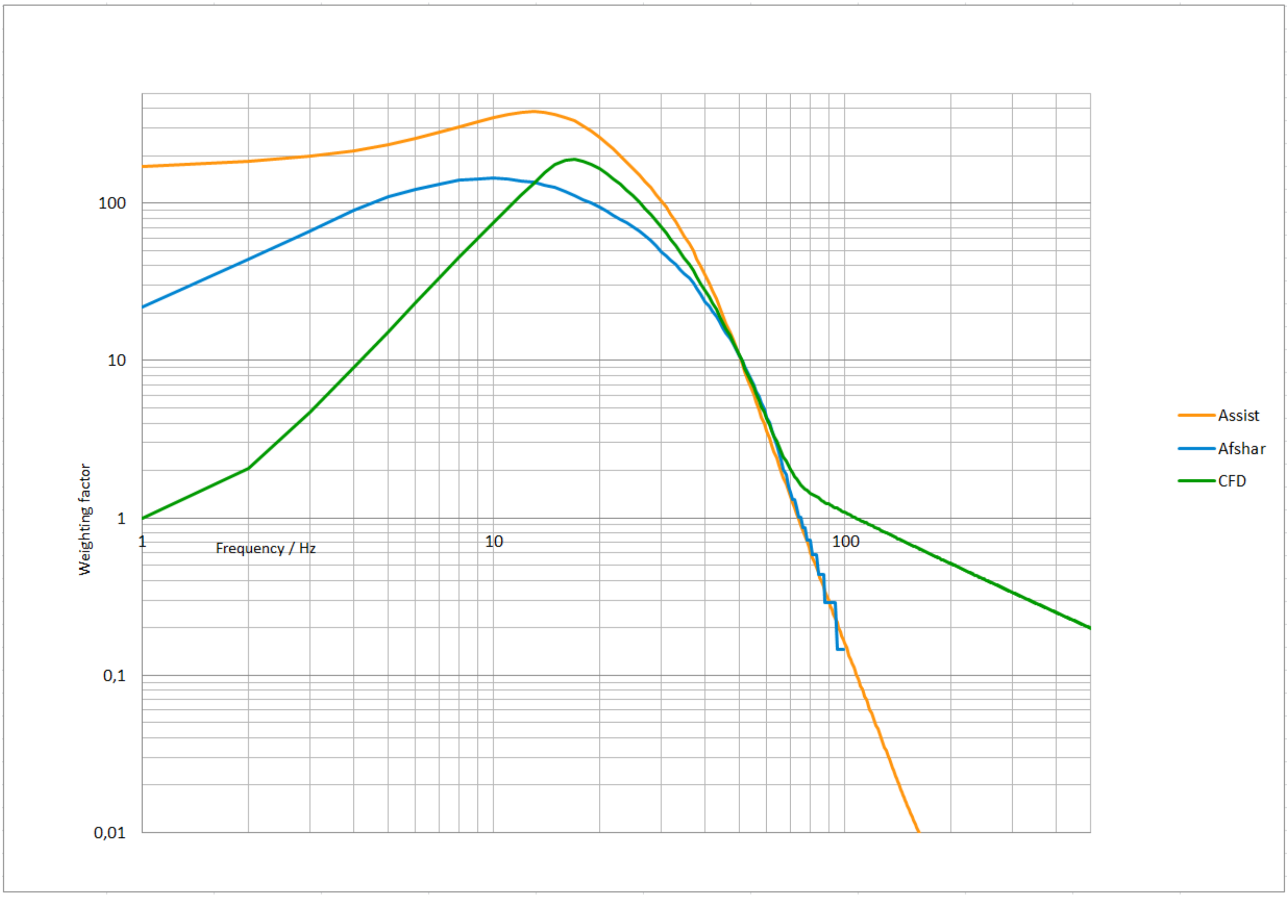

Figure 1: Characteristics of frequency-dependent weightings

The base of frequency dependent weightings are studies in which the subjects are situated rested (no body and no eye movements). While this may serve as a guide, however, this is not applicable to real-life conditions, because e.g. stroboscopic effects at double mains frequency are noticeable even at slightest movements and cause discomfort, partly even incoordination. It is also known that frequencies up to 300 Hz are passed on from the retina to the brain and processed only there, which can lead to a load that is associated with fatigue and headache[6].
At frequencies above about 90 Hz the phantom array effect plays a role[7], which is solely considered in the CFD-characteristic as figure 1 shows. The transition from the perceptible at rest nonlinear frequency range to the perceptible during agitation linear range is designed fluently. The range below 10 Hz in the CFD-characteristic is weighted lower in order to avoid the overestimation of residual FFT leakage effects in practical measurements in this frequency region (also after application of a FFT window).

As the final value the CFD provides a simple percentage by forming the root mean square of all single normalized to DC and frequency dependently weighted frequency components. The range may extend from 0% to over 1000%, which is due to the waveform and the resulting frequency components. Spikes, in contrast to a sinusoid contain many frequency components with very high amplitude at 100%, which adds up accordingly.
This way the requirements of taking the curve shape and the contrast into account are met.

2.3. Assessment of the light quality

The CFD is a general measure of modulated light. Table 1 shows that its simple percentage value permits categorization according to a traffic light system:

(dark green)	0 < CFD < 1% Flicker free Color: Dark green	Practically free from modulation, a virtually pure DC component.
(dark green)	1% < CFD < 10% Low flicker Color: Dark green	Modulation virtually imperceptible.
(yellow green)	10% < CFD < 25% Acceptable Color: Yellow green	Modulation may be noticeable but acceptable.
(yellow)	25% < CFD < 50% Moderate Color: Yellow	Modulation may be perceived and possible discomfort after prolonged exposure, increased eye strain at work.
(orange)	50% < CFD < 75% Strongly affected Color: Orange	Beginning of stroboscopic effects at mains frequency, probably perceptible by more than 50% of the population and discomfort after prolonged exposure, barely suitable for work.
(red)	CFD > 75% Extremely affected. Color: Red	Stroboscopic effects, probably perceived by more than 75% of the population, impaired physical condition (headache, malaise) after prolonged exposure, risk of epileptic seizure, unsuitable for the correct perception of motion sequences. Dangerous for jobs with rotating or cycling parts.

Table 1: CFD categorisation according to a traffic light system

According to DIN EN 12464-1/-2 mains frequency dependent stroboscopic light (CFD ≥ 50%) should be avoided at workplaces. Light sources that do not meet this standard, should actually already now point out an obstacle to using: "Unsuitable for work".

A special case of the light modulation is the light flickering of illuminants, which is modulated at the double mains frequency. This is currently being discussed especially because many of the illuminants on the market (especially many of the new LED-filament-bulbs from China) have massive stroboscopic effects: The modulation depth is 100%, the CFD > 75%. For this special case, the method according to IES: RP-16-10[3] with the %Flicker indication has spread a bit. This, however, only allows a statement about the quality of light with respect to the modulation when the light is modulated practically with only a single frequency, i.e. hardly having harmonic components. For a mixture of frequencies, RP-16-10 has no calculation rule. In practice, the main modulation frequency is twice the mains power supply frequency, but in general, the light emission with a large amplitude or dimmed light source is non-sinusoidal.

As to be seen in Figure 2 according to IEEE 1789, there are frequency-dependent limits for the classification of a light source in "low risk" or "no effect". In the presence of frequency mixtures (which usually is the case), however, the calculation basis is missing. To IEEE 1789 it makes no difference whether the modulation of a light source is performed with spikes, a sinusoid or a PWM with a duty ratio of ≥ 95%. It is obvious that this very well makes a difference in practice.

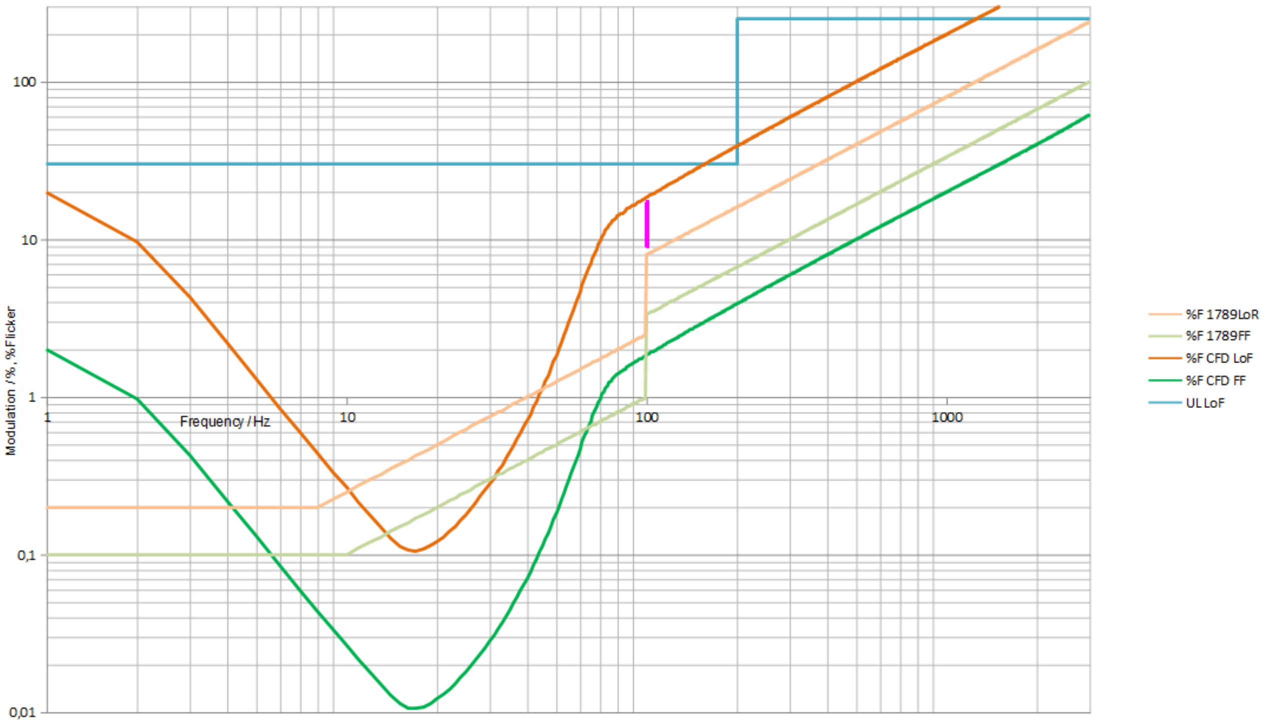

Figure 2: Characteristics of frequency-dependent thresholds

Figure 2 represents the following rating limits of %Flicker function of frequency:

- Weakly coloured: Limits according to IEEE 1789,
  top: threshold from "risky" to "low risk",
  below: threshold from "low risk" to "no effect"
- Heavily coloured: CFD limits transferred from table 1 to %Flicker,
  top: threshold from "acceptable" to "low flicker",
  below: threshold from "low flicker" to "flicker free"
- Blue: Limits according to Underwriters Laboratories (UL):
  Threshold to "low flicker"
- Magenta mark: Light modulating area for an incandescent lamp at 50 Hz mains frequency.

In the diagram it is apparent that the CFD limits for the area "low flicker" are more tolerant than the limits according to IEEE 1789, but much sharper than the UL limits. The light of incandescents applies to IEEE 1789 already considered high risk; although 100 years of experience show that there is no risk. The predicate "flicker free" is with the CFD as a measure more challenging than IEEE 1789.

An explanation to plausibility is required for IEEE 1789 as there is a qualitative leap from 99 Hz to 100 Hz by a factor of 3.3. Physiology is hardly the reason, the transition would be smooth.

When evaluated by UL the threshold to "low flicker" at a modulation of 30% at 20 Hz is extremely doubtful, which is also a great contradiction compared to IEEE 1789 with a limit of 0.5% as a factor of 60.

2.4. Examples of measurement results

The following figures show excerpts of light emission curves with light modulations of different light sources each sampled with the system by Der Lichtpeter at a frequency of 500 kHz and a sampling time of 1.0 seconds.

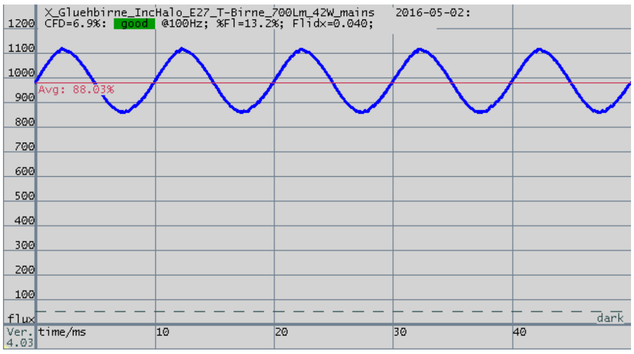

Figure 3: Incandescent bulb

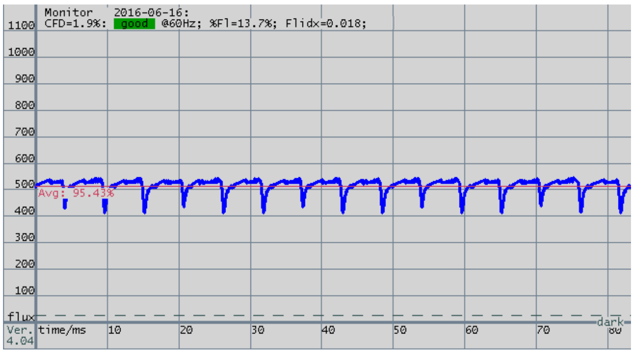

Figure 4: Computer monitor

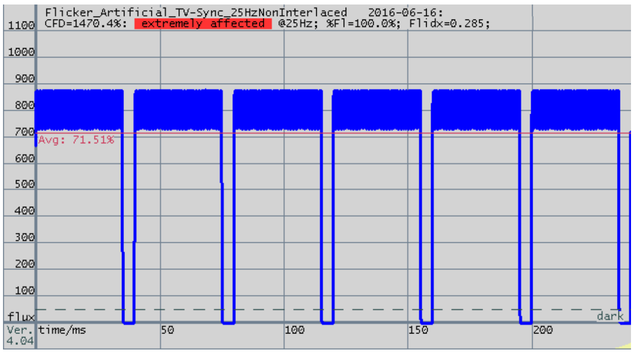

Figure 5: TV screen non-interlaced

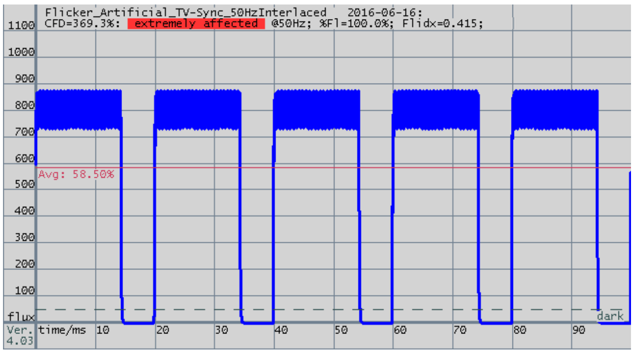

Figure 6: TV screen interlaced

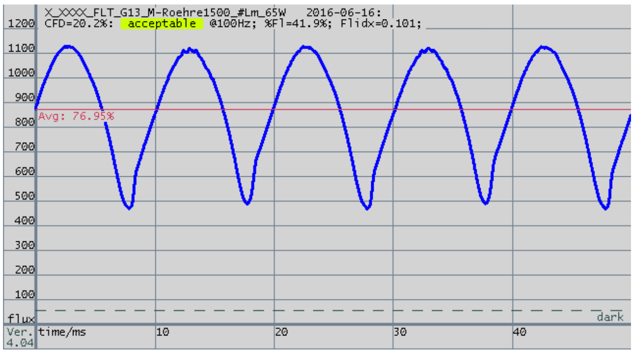

Figure 7: Fluorescent tube with MB

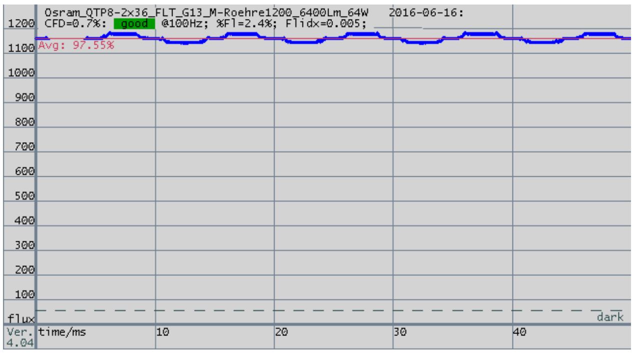

Figure 8: Fluorescent tube with EB

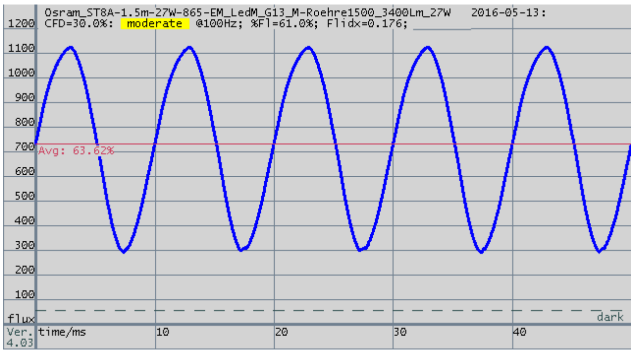

Figure 9: LED illuminant with moderate EB on mains power supply

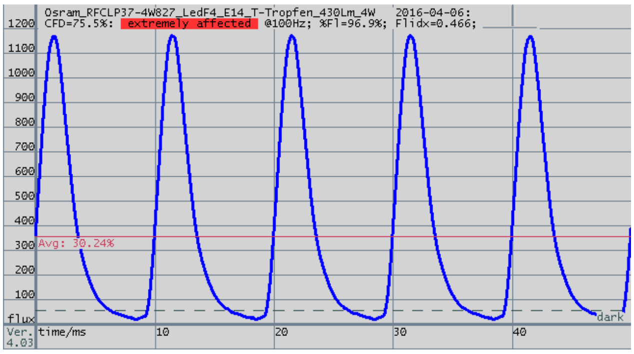

Figure 10: LED illuminant with insufficient EB on mains power supply

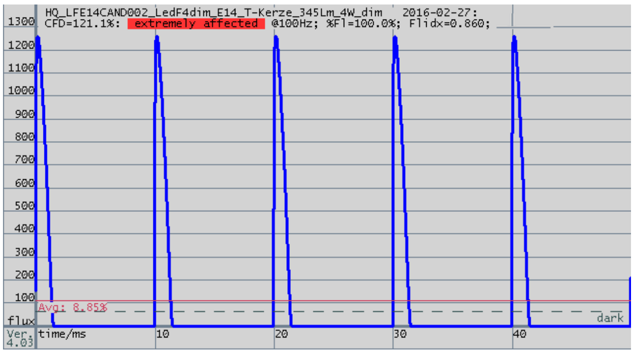

Figure 11: LED illuminant with insufficient EB dimmed to 25%

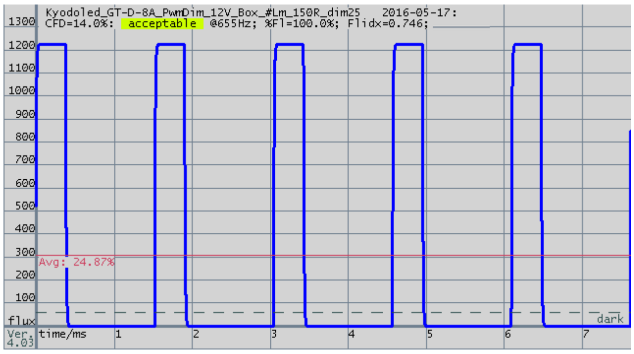

Figure 12: LED without EB dimmed to 25% via PWM dimmer at 655 Hz

Table 2: Figures of light emission curves

3. Conclusions

To measure and assess light with respect to all modulations acting on humans and other beings all frequency components up to 20 kHz have to be taken into consideration. Consequently, the calculation is only possible on the frequency domain, whereas each individual frequency has to be weighted according to the impact on humans. The **C**ompact **F**licker **D**egree **CFD** by Der Lichtpeter meets this requirement and is applicable to any light source. The CFD with a single percentage is an easy-to-use measure of the user's hand and thus allows a quantitative assessment of a light source with respect to the light modulation. By categorizing according to a traffic light system the optimal quality levels classification can be made.

With the CFD as a true measure, the indication of the CFD in the technical data should become mandatory and standard limits should be preset.

Der Lichtpeter offers a service to have illuminants and other light sources measured regarding their light modulation. In addition to the CFD the report provides the results of all other existing measurement methods to enable a comparison.

Manufacturers and distributors will benefit using this service and will be placed better on the market by offering products professionally certified as low flicker or flicker free. Also to improve products, it is important to keep an eye on the light modulation and perform appropriate measurements.

4. References

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