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# LED SPECTRAL AND POWER CHARACTERISTICS UNDER HYBRID PWM/AM DIMMING STRATEGY

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**Abstract --** In order to dim LEDs the pulse width modulation (PWM) or amplitude modulation (AM) dimming scheme is typically used. Previous studies show that these dimming schemes can have opposite effects on diodes peak wavelength shift. An experimental study was conducted to test the behavior of InGaN diodes and phosphor-converted white diodes under hybrid PWM/AM modulation. Feed forward control schemes that provide stable peak wavelength position during dimming and the ability to compensate the thermally induced color shifts and the decrease of the luminous flux are investigated.

**Index Terms --** Light-emitting diodes, amplitude modulation, pulse width modulation.

## I. INTRODUCTION

Light emitting diodes are commonly used in signage and display applications. Due to the decreasing price of high power diodes, LEDs are slowly entering general lighting market [1]. Their advantages over the traditional light sources include small size, long lifetime and ability to produce pure, saturated colors with high luminous efficiency.

Dimming is an essential feature in many lighting applications and is necessary in RGB LED based lamps in order to change the light color. Color is controlled by adjusting the relative intensities of primary LEDs in the luminaire. Typically LEDs were dimmed with either pulse width modulation or amplitude modulation but recent development [2]-[3] shows that combining these methods and driving the diodes with different current shapes can have significant difference on spectral and power characteristics of the diode. This paper shows the implications of using a hybrid PWM/AM driving technique.

In order to quantify the performance of an LED one needs to distinguish between electrical, radiometric, photometric and colorimetric properties.

Electrical energy is converted to electromagnetic radiation by means of electroluminescence. The relation between radiometric power and electrical power is defined by power efficiency [4]:

$$\eta_{\text{power}} = \frac{P_{\text{rad}}}{I_f \cdot V} \quad (1)$$

where  $P_{\text{rad}}$  is the optical power emitted from LED into free space,  $I_f$  is diode forward current and  $V$  is diode forward voltage.  $\eta_{\text{power}}$  defines the percentage of input power that is converted into photons. The rest of the input power is converted into heat and thus increases the diode temperature and lowers its performance.

Generated photons are converted into sensation of color and light intensity by the eye. These sensations are quantified by means of color coordinates (eg.  $x$ ,  $y$  in CIE 1931 color space) and luminous flux ( $F$ ) respectively. The efficiency of conversion from electrical input power to luminous flux is called luminous efficiency [4], measured in lm/W

$$\eta_{\text{lum}} = \frac{F}{I_f \cdot V} = \frac{683 \cdot \int P_{\text{rad}}(\lambda) V(\lambda) d\lambda}{I_f \cdot V} \quad (2)$$

where  $V(\lambda)$  is an eye sensitivity function also called luminous efficiency function (Fig. 1) and  $P_{\text{rad}}(\lambda)$  is the spectrum of examined light source. Luminous efficiency is strongly dependent on human eye properties and the shape of the light source spectrum.

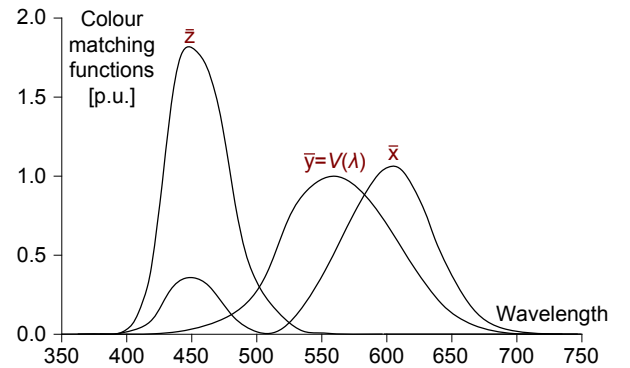


Fig. 1. CIE 1931  $\bar{x}$ ,  $\bar{y}$  and  $\bar{z}$  color matching functions. Color matching function  $\bar{y}$  is equal to the eye sensitivity function  $V(\lambda)$ .

The sensation of color can be represented as color coordinates in a color space. In 1931, CIE standardized the measurement of color by introducing three color matching functions  $\bar{x}$ ,  $\bar{y}$  and  $\bar{z}$  (Fig. 1). Weighting the light source spectrum with color matching functions yields three scalar tristimulus

values:  $X$ ,  $Y$  and  $Z$ . The chromaticity coordinates of the light source are calculated according to

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}. \quad (3)$$

Different dimming schemes will have different effects on diodes spectral properties [5]-[7] e.g. AlGaInP diodes will experience spectrum shifts towards shorter wavelengths with both AM and PWM while InGaN diodes experience opposite shifts under these methods (Fig. 2). This paper shows the possibility of using this phenomenon in order to achieve more stable color point during dimming.

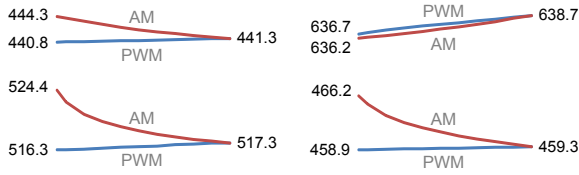


Fig. 2. Peak wavelength position under PWM and AM dimming schemes for white phosphor converted LED (top, left), red AlGaInP diode (top, right) and green and blue InGaN diodes (bottom: left and right, respectively).

## II. LED DIMMING SCHEMES

Two dimming schemes are the most popular in the industry: pulse width modulation and amplitude modulation (sometimes referred to as continuous current reduction).

Under pulse width modulation the diode is turned on and off with fixed frequency and variable duty cycle (Fig. 3). The duty cycle  $d$  defines the relation of on-time of the diode to the period of the cycle  $T$ . Forward current of the diode is set to the maximum value defined by the manufacturer  $I_{f,max}$  and the light intensity is controlled by modifying the duty cycle ratio.

$$I_{f,avg} = I_{f,max} \cdot \frac{t_{on}}{T} = I_{f,max} \cdot d \quad (4)$$

PWM scheme offers high dimming ratio and almost linear flux to duty cycle ratio. On the other hand, pulse width modulation dimming will generate radiated EMI noise by the converter—LED current loop because of the pulsed nature of the driving current.

Amplitude modulation uses the variable DC current to dim the LED (Fig. 3). At lower current concentrations LED's efficacy tends to increase, therefore the AM dimming is not linear. Also significant chromaticity shifts occur at very low forward current. This is why PWM dimming is typically used by the industry.

Recently [2]-[3] proposed a generalized driving technique for LEDs. A variation of this method (hybrid PWM/AM dimming) was chosen to be investigated because most of the existing LED drivers on the market are capable of controlling a diode by means of PWM and AM at the same time with little or no modifications. In this modulation both peak current during on-time in a PWM period and duty cycle are controlled in

order to obtain desired average forward current.

$$I_{f,avg} = I_{f,peak} \cdot \frac{t_{on}}{T} = I_{f,peak} \cdot d \quad (5)$$

The product of peak current  $I_{f,peak}$  and duty cycle  $d$  will determine the value of average current. Different combinations of peak current and duty cycle can produce the same value of average current as seen in Fig. 3 but, as experimental data show, can have different effect on diode's properties. In the next chapters the spectral and power properties of PC white LEDs and InGaN LEDs will be analyzed.

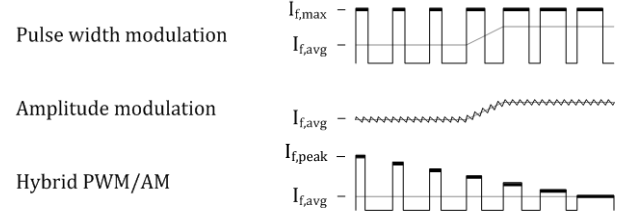


Fig. 3. Concept of different LED dimming schemes.  $I_{f,max}$  is the maximum forward current of an LED. Under PWM, the average current is controlled by the duty cycle. Under AM the average current is a directly controlled variable. Hybrid PWM/AM uses variable peak current and variable duty cycle to control the average forward current. Different combinations of peak current and duty cycle can be used to obtain the same value of the average current.

## III. TEST SETUP

Diodes' properties were measured in a test setup consisting of an LED driver capable of supplying up to 1A pulsed current, NI cDAQ data acquisition system, Arroyo Instruments 5310 temperature controller, CAS 140 CT spectrometer and an integrating sphere. Reference for peak current and duty cycle were generated by NI 9201 voltage source module. Current and voltage of the LEDs were measured with NI 9221 24-bit ADC. Voltage and current measurements were gathered over 20ms period to compensate the 50Hz grid noise.

## IV. INGAN DIODES

Spectral properties of high power InGaN LEDs under PWM and AM dimming schemes have been characterized by Gu et al. [6]. The study shows that InGaN LEDs typically experience opposite peak wavelength shifts with pulse width modulation and amplitude modulation. The hybrid PWM/AM modulation could therefore compensate the shift and make the color point more stable.

### A. Constant peak wavelength

An experiment was conducted to confirm this hypothesis. Under PWM dimming scheme, diodes were driven with 0.1, 0.2...0.9, 1.0 duty cycle. Under AM, diodes were driven with 0.14, 0.21...0.63, 0.7A DC current. Diodes' input and output power, flux, color coordinates and peak wavelength were saved. Experiments were repeated at three different heatsink temperatures: 20, 40 and 60°C to check whether the magni-

tude of peak wavelength shift is temperature dependent.

In order to verify if hybrid PWM/AM dimming technique can keep the peak wavelength stable, the duty cycle was set to arbitrary value and then the peak current was adjusted so that the peak wavelength value would match the nominal value.

Fig. 4 and Fig. 5 show the peak wavelength shifts at different heatsink temperatures for green and blue diodes respectively. The results show that the relative shift is the same at all measured temperatures. Stable peak wavelength value was obtained for the corresponding duty cycle and peak current level pairs that are plotted in Fig. 6.

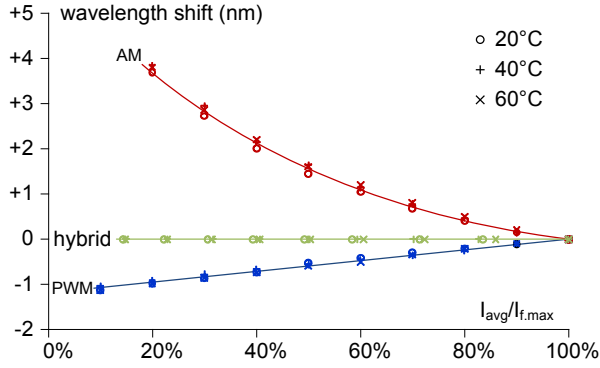


Fig. 4. Peak wavelength shifts of green diode when dimmed with PWM, AM and hybrid dimming strategies at different heatsink temperatures.

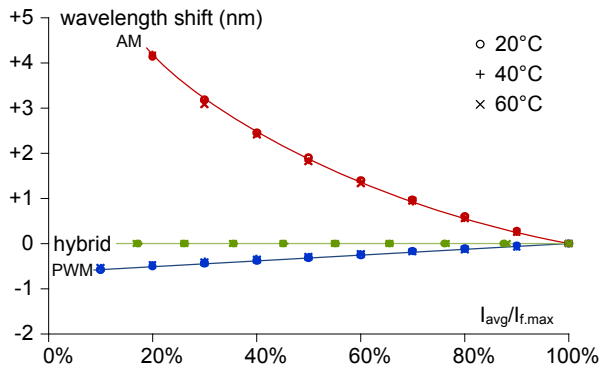


Fig. 5. Peak wavelength shifts of blue diode when dimmed with PWM, AM and hybrid dimming strategies at different heatsink temperatures.

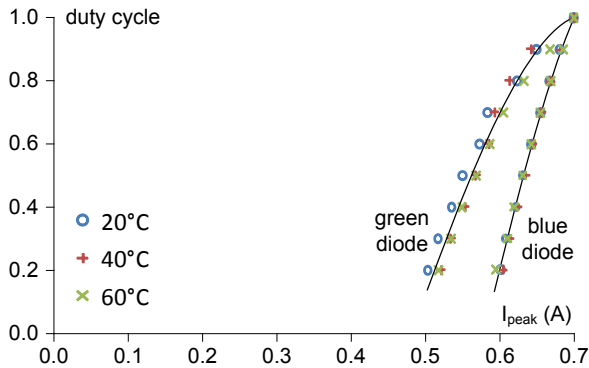


Fig. 6. Relation between peak current and duty cycle for hybrid dimming strategy that maintains the peak wavelength position.

The relation between the duty cycle and the peak current for obtaining stable peak wavelength position is not dependent on the temperature therefore a feed forward compensation can be used to calculate one parameter from the other. Measured data points fitted to the second order polynomial yield the following relations:

$$\begin{aligned} I_{f,peak,green} &= 0.1739 \cdot d^2 + 0.0079 \cdot d + 0.5109 \\ I_{f,peak,blue} &= 0.0410 \cdot d^2 + 0.0727 \cdot d + 0.5851 \end{aligned} \quad (6)$$

Therefore, if peak current calculated from (6) is used as current command for LED driver and  $d$  value is used to generate PWM signal, the diode's peak wavelength will remain constant during dimming.

Color shifts under all three dimming schemes are presented in Fig. 7 and Fig. 8 for green and blue diodes respectively. Opposite peak wavelength shifts under PWM and AM methods together with a changing spectrum shape creates color shifts in different directions. Behavior of the color point under Hybrid PWM/AM method has two distinctive features: the shift direction follows the shape of MacAdam ellipses more closely and in case of the blue LED the magnitude of the shift is strongly decreased.

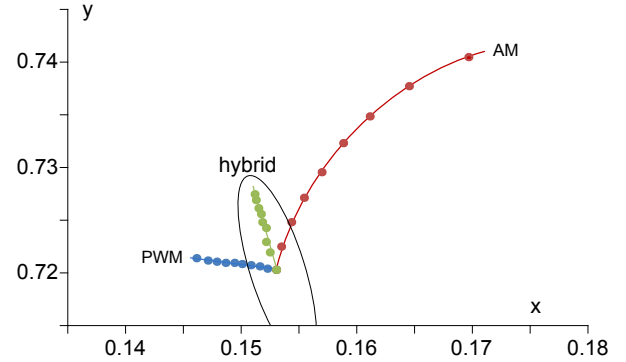


Fig. 7. Color shifts of green diode when dimmed with PWM, AM and hybrid dimming strategies. MacAdam ellipse ( $x = 0.150, y = 0.680$ ) shown to estimate the noticeable color difference during dimming.

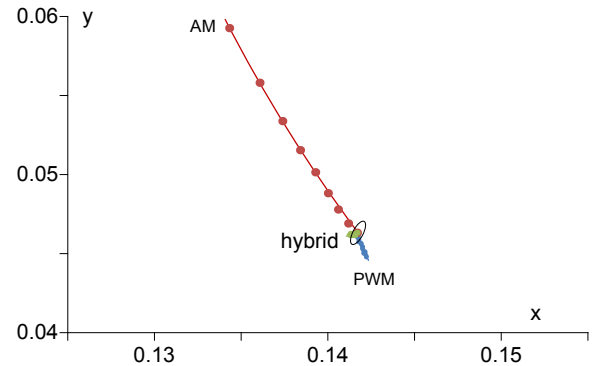


Fig. 8. Color shifts of blue diode when dimmed with PWM, AM and hybrid dimming strategies. MacAdam ellipse ( $x = 0.160, y = 0.057$ ) shown to estimate the noticeable color difference during dimming.

Although the peak wavelength can be kept constant during dimming with this method, the thermally induced shifts (+0.025nm/K and +0.047nm/K for blue and green diodes, respectively) are not compensated.

Luminous efficacy change due to spectrum shift is noticeable only for AM dimming (Fig. 9). For both PWM and hybrid dimming mechanisms the change of  $\eta_{lum}$  is mainly due to the change in power efficiency.

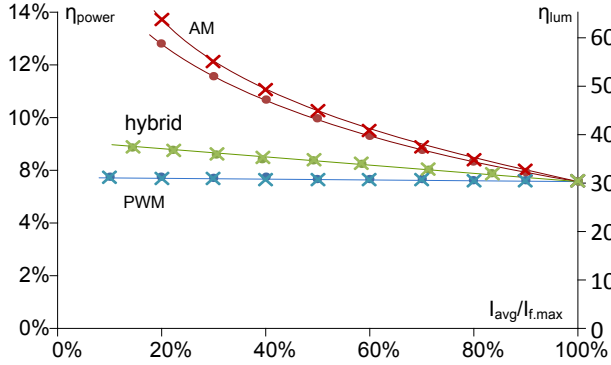


Fig. 9. Power efficiency (●) and luminous efficiency (×) of green diode dimmed with PWM, AM and hybrid techniques. Big spectral shifts during AM dimming in the direction of increased eye efficiency yields an increased luminous efficiency.

### B. Constant flux and peak wavelength

As two variables are used to control the diode: peak current and duty cycle, the number of constraints in the system can be increased. An experiment was conducted to measure the color difference when both luminous flux and peak wavelength position are controlled by hybrid modulation. The performance of this control method is compared to PWM and AM dimmed diode where only the flux was controlled. The control system was tested in 20...70°C heatsink temperature range.

Color shifts under hybrid dimming strategy are gathered in Table 1. Color difference is quantified by chromaticity difference in CIE 1976 color space according to equation

$$\Delta u'v' = \sqrt{(u_2' - u_1')^2 + (v_2' - v_1')^2} \quad (7)$$

where  $(u_1', v_1')$  and  $(u_2', v_2')$  are the chromaticity points of two color points [7]. Heatsink temperature and corresponding peak current and duty cycle needed to obtain the stable flux and peak wavelength values are plotted in Fig. 10.

TABLE 1

COLOR SHIFTS OF HYBRID DIMMED BLUE DIODE UNDER CONSTANT FLUX AND PEAK WAVELENGTH POSITION CONTROL

$T_{hs}$ [°C]	duty	$I_{peak}$	peak wl.	flux	$u'$	$v'$	$\Delta u'v'$
20	1.000	0.400	460.93	10.00	0.1675	0.1355	0.00000
30	0.963	0.433	460.93	10.01	0.1678	0.1355	0.00026
40	0.918	0.470	460.93	10.00	0.1679	0.1355	0.00039
50	0.866	0.516	460.93	10.01	0.1683	0.1353	0.00086
60	0.810	0.570	460.93	10.00	0.1687	0.1351	0.00123
70	0.755	0.634	460.93	10.01	0.1691	0.1349	0.00172

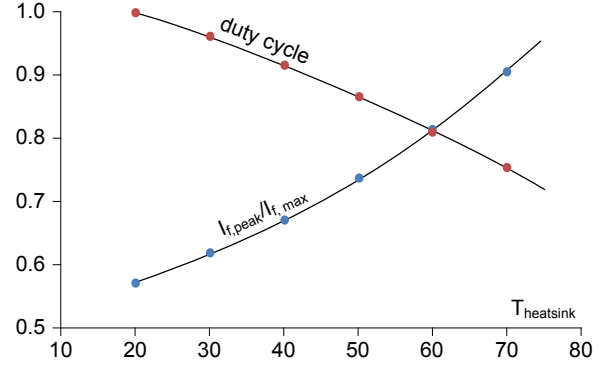


Fig. 10. Duty cycle and relative peak current values for hybrid PWM/AM dimming used to obtain stable flux and peak wavelength position.

Both peak current and duty cycle can be mathematically described as a function of the heatsink temperature creating a temperature feed forward control system:

$$\begin{aligned} I_{f,peak} &= 0.00004 \cdot T_{hs}^2 + 0.0011 \cdot T_{hs} + 0.3637 \\ d &= -0.00002 \cdot T_{hs}^2 - 0.0028 \cdot T_{hs} + 1.0671 \end{aligned} \quad (8)$$

where  $T_{hs}$  is the heatsink temperature in degrees Celsius. The heatsink temperature has to be either measured directly close to the diode or estimated.

With the increase of the temperature the duty cycle was decreased and the peak current increased. Therefore, the usable range is limited by the maximum duty cycle at lower temperatures and maximum forward current at high temperatures. When the experiment was repeated for higher value of the luminous flux (12.15lm) for the same diode, the temperature range, where the parameters were kept constant, lowered to 20...56°C. Therefore, in order to achieve high temperature range a diode has to be overrated.

Both PWM and AM dimmed blue LED experienced much higher color shifts than hybrid dimmed LED as seen in Table 2 and Table 3 respectively.

TABLE 2

COLOR SHIFTS OF PWM DIMMED BLUE DIODE UNDER CONSTANT FLUX CONTROL

$T_{hs}$ [°C]	duty	$I_{peak}$	peak wl.	flux	$u'$	$v'$	$\Delta u'v'$
20	0.622	0.700	459.18	10.00	0.1742	0.1248	0.00000
30	0.640	0.700	459.44	10.00	0.1735	0.1262	0.00151
40	0.655	0.700	459.70	10.00	0.1729	0.1276	0.00301
50	0.670	0.700	459.98	10.00	0.1720	0.1291	0.00479
60	0.655	0.700	460.29	10.00	0.1712	0.1309	0.00679
70	0.696	0.700	460.59	10.00	0.1703	0.1327	0.00878

TABLE 3

COLOR SHIFTS OF AM DIMMED BLUE DIODE UNDER CONSTANT FLUX CONTROL

$T_{hs}$ [°C]	duty	$I_{peak}$	peak wl.	flux	$u'$	$v'$	$\Delta u'v'$
20	1.000	0.401	460.91	10.00	0.1676	0.1352	0.00000
30	1.000	0.415	461.03	10.00	0.1672	0.1359	0.00073
40	1.000	0.427	461.22	10.00	0.1669	0.1370	0.00187
50	1.000	0.438	461.42	10.00	0.1663	0.1383	0.00331
60	1.000	0.449	461.63	10.00	0.1658	0.1396	0.00470
70	1.000	0.458	461.90	10.00	0.1652	0.1409	0.00613



## V. PHOSPHOR CONVERTED WHITE DIODES

Dyble et al. [5] analyzed white LED's chromaticity shifts under PWM and AM dimming. Both methods yielded in noticeable color shift when dimmed below 10%. PWM performed better than AM producing color shift within 2-step MacAdam ellipse.

Phosphor converted white diode's spectrum consists of two separate peaks: one from blue diode and the other phosphor converted yellow. The yellow part is a function of phosphor excitation and emission spectra and the blue diode spectrum. The white color is generated by mixing the blue LED light with yellow phosphor light, therefore the position of white color point does not rely exclusively on the peak wavelength position.

The behavior of the color point was measured during AM and PWM dimming. Fig. 11 shows that the color shifts lie on the same line but have opposite directions.

The vector of thermally induced color shift can be resolved along the axis of dimming color shifts yielding two parallel and perpendicular vectors:  $T_{s,\parallel}$  and  $T_{s,\perp}$ . Hybrid dimming strategy should compensate the parallel component leaving only perpendicular  $T_{s,\perp}$  color shift.

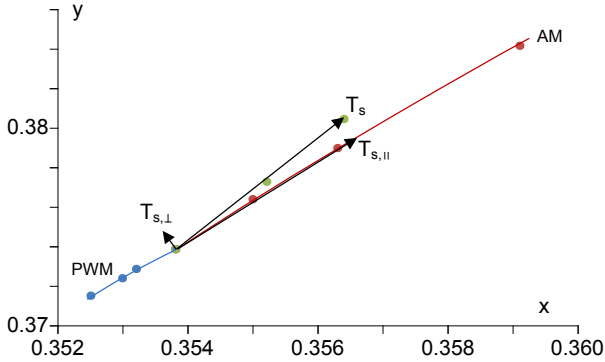


Fig. 11. Color shifts of phosphor converted white diode when dimmed with PWM and AM dimming strategies. Color shifts  $T_s$  due to heatsink temperature changes (20→60°C)

The theory was verified experimentally. The parallel component of thermally induced color shift was compensated by adjusting both peak current and duty cycle.

TABLE 4

COLOR SHIFTS OF HYBRID DIMMED WHITE DIODE. THE FLUX WAS KEPT CONSTANT AND THE PARALLEL COMPONENT OF THERMALLY INDUCED COLOR SHIFT WAS COMPENSATED.

$T_{hs}$ [°C]	duty	$I_{peak}$	flux	$u'$	$v'$	$\Delta u'v'$
20	1.000	0.411	53.3	0.2085	0.4981	0.00000
30	0.905	0.485	53.3	0.2085	0.4981	0.00000
40	0.796	0.597	53.3	0.2084	0.4982	0.00011
50	0.716	0.712	53.3	0.2083	0.4982	0.00021

Heatsink temperature and corresponding peak current and duty cycle needed to cancel the thermally induced color shift are shown in Fig. 12. Peak current and duty cycle described as a function of the heatsink temperature:

$$\begin{aligned} I_{f,peak} &= 0.0001 \cdot T_{hs}^2 + 0.003 \cdot T_{hs} + 0.3088 \\ d &= 0.00004 \cdot T_{hs}^2 - 0.0122 \cdot T_{hs} + 1.2309 \end{aligned} \quad (8)$$

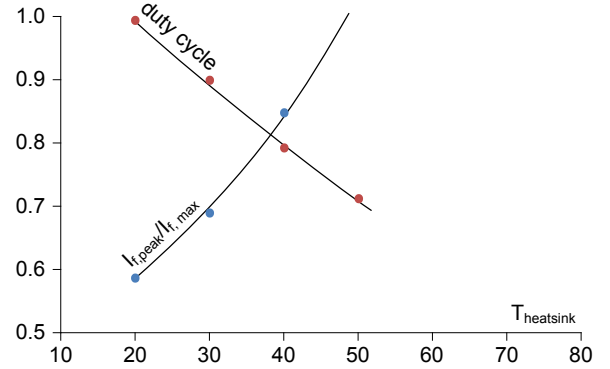


Fig. 12. Duty cycle and relative peak current values for hybrid PWM/AM dimming used to cancel the thermally induced color shift of white diode.

## VI. CONCLUSIONS

Hybrid PWM/AM dimming scheme provides an increased control over InGaN diodes and phosphor converted white diodes. Opposite peak wavelength shifts phenomenon was used for the InGaN diodes to compensate the color shifts during dimming. The change of the position of the spectrum has a big impact on errors in the luminaries with optical feedback. Therefore application of the hybrid dimming method in those luminaires should be investigated.

In PWM and AM only one parameter can be controlled. Hybrid dimming has two control variables therefore two parameters can be controlled. This feature is especially useful for white phosphor-converted LED based luminaires where luminous flux can be kept constant and the color shifts due to temperature change can be minimized.

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