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LED directivity measurement in situ

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Abstract

The paper presents the technique of LED directivity measurement in situ. A LED far-field pattern (FFP) can be measured quickly without dismantling the LEDs from the tile. The positioning device has been replaced by lighting a single LED in a tile, so the desired inspection angle has been obtained. Irradiance data then has been corrected for distance and sensor directivity. The resulting data set has been fitted with the approximation function. The obtained approximation is the representative of the average LED FFP. Brief analysis of an approximation function has been carried out. Four simple functions have been considered as candidates for such approximation. The L2-norm of the error between the original and fitted function was considered as an approximation quality criterion. Gaussian approximation has the best performance. For in situ technique performance evaluation, several sample tiles have been measured and the obtained outcome has been compared against goniometry results. The L2-norm of the LED FFP intensity error and viewing angle error are presented.

Keywords: LED far-field diagram; LED directivity measurement; LED display measurement

1. Introduction

A light emitting diode (LED) video screen is an unbeatable source for video information presentation on large scale, when a wide viewing angle and bright image are needed [1].

LED directivity defines directional properties [2] of the assembled screen. The best way for screen performance prediction would be to measure the discrete LEDs before they are assembled to a tile or at least similar LEDs that are from the same lot as the ones already assembled. Then total screen response can be calculated using simple equations. In case of system integration or components outsourcing, LED screen tiles come assembled. Generally, manufacturers specify the directivity parameters of the LEDs used, therefore, the resulting display response can be estimated applying a single LED directivity pattern. However, sometimes, there is a need to confirm LED directivity parameters. This is the case when there is a suspicion that a tile supplier has violated the declared directivity or single LED measurements are impossible, or a tile manufacturer is not able to indicate the directivity. Then LED directivity measurement in situ is required.

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2. Problem description

LED application for large scale LED video screen imaging is analyzed. In order to estimate the performance of the total product such as a LED sign or video display, measurements of LED directivity properties are used [3–5].

Spatial directivity [4,5] of LED radiation intensity usually named as a far-field pattern (FFP) is one of the essential parameters in order to evaluate LED suitability for large video screen applications (refer to Fig. 1).

To describe the LED FFP quality [4], two parameters are used:

- Full width at half max angle $2\Theta_{0.5}$ where source intensity is dropping to half of the peak emission;
- maximum emission or peak emission direction Θ_{peak}.

Both are measured relatively to a mechanical axis. For $2\Theta_{0.5}$ and Θ_{peak} explanation, refer to Fig. 2.

What concerns the resulting video screen response, $2\Theta_{0.5}$ angle can be used to determine the screen visibility angle, whereas angle Θ_{peak} and $2\Theta_{0.5}$ variation can be applied for screen image purity prediction. Using LED FFP $I(\Theta)$, the resulting complete LED video screen radiance FFP $B_{SC}(\Theta)$ can be calculated [6].

$$B_{SC}(\Theta) = \frac{I(\Theta)}{\cos(\Theta)}. \quad (1)$$

A screen FFP [2] differs from individual LED FFP, i.e. usually it is wider. Refer to Fig. 3 for the resulting screen FFP obtained by applying Eq. (1) for data in Fig. 1.

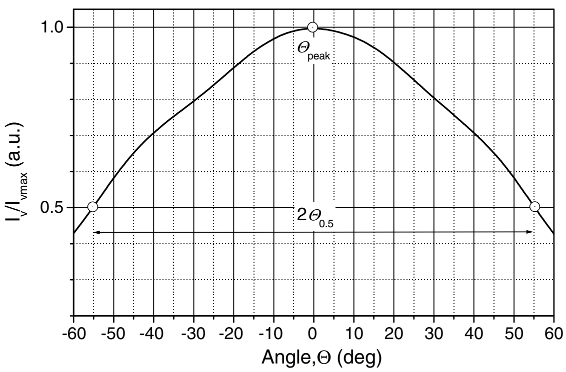

Fig. 1. LED FFP (intensity spatial distribution) in Cartesian coordinates.

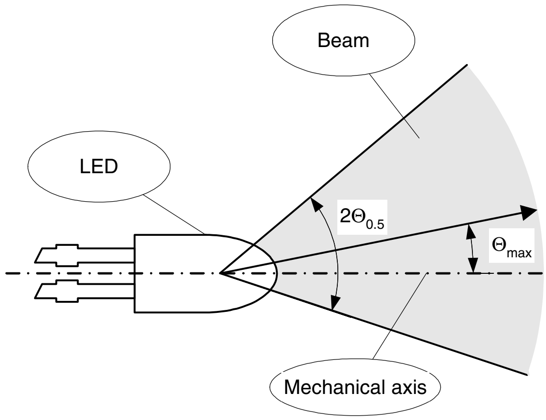

Fig. 2. Explanation of Θ_{peak} and $2\Theta_{0.5}$.

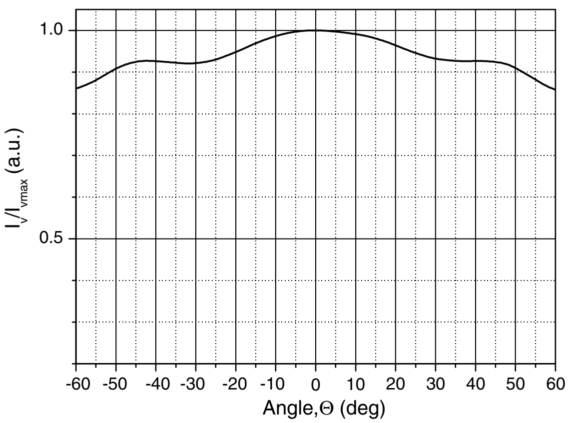

Fig. 3. Calculated screen FFP in Cartesian coordinates.

A LED FFP defines the screen directional performance. It should be noted that LED always has some directivity variation. With the individual LED FFP describing the LED properties, screen luminance is the combined response of all the LEDs used in screen construction. Therefore, the average response of several (N) LED FFP $I_i(\Theta)$ should be used in Eq. (1) for screen directivity calculation:

$$\bar{I}(\Theta) = \frac{\sum_{i=1}^{N} I_i(\Theta)}{N}. \quad (2)$$

A varying LED FFP should result in different screen responses. In some cases, a smooth and wide-angle screen directivity response is obtained, whereas in other cases, screen intensity variation is quite considerable. Furthermore, if a color video screen is used, directivity for all three colors shall match. For instance, if a FFP for a red LED is wider, the resulting screen image will appear reddish if viewed at some angle, even if LED intensity in a right direction has been matched for perfect white balance. Violation of the declared LED directivity can significantly degrade the display performance. If a LED FFP is already available, the screen response can be predicted. But sometimes, directivity measurements are required when assembled tiles are available solely or tiles have to be inspected for quality confirmation. Therefore, the solution was needed to measure the assembled LED video screen tile LED FFP.

3. Solution

If Eq. (1) is applied for screen directivity calculation using the average from individual LEDs, then it can be reversed for the case when the LED response has to be obtained from screen directivity measurements.

A few assumptions have been made in order to establish a measurement technique:

- To manufacture a single tile, LEDs of the same type are used;
- only the central part of a LED FFP within $2\Theta_{0.5}$ is of interest;
- within a tile, normal distribution of LED directivity is observed;
- an average response of all LED FFPs used in a tile defines screen directivity.

For screen directivity measurement, mechanical positioning equipment is needed. Furthermore, if screen size is limited to a single tile then some errors will be introduced in brightness estimation.

After lighting only one LED in a tile, this LED is visible at some angle from a given reference point. Other LED will be viewed at a different angle from the same reference point. Choosing the right position of this reference point would allow establishing a set of angles to the LED required for construction of a FFP. When LEDs are lit in a sequence, the irradiance at this reference point can be measured using a photosensor (refer to Fig. 4). This can be converted to radiometric intensity and subsequently to luminous intensity.

In order to obtain sufficient angles, the sensor distance to the screen surface r_{max} should be

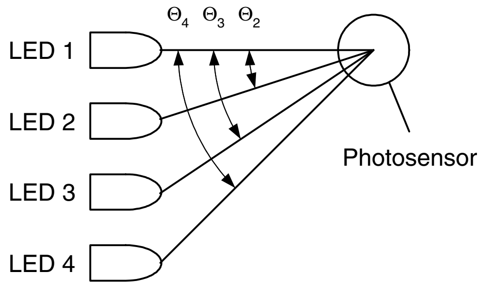

Fig. 4. Measurement system structure.

$$r_{max} = \frac{d_{max}}{2\tan\left(\frac{2\Theta_{0.5}}{2}\right)}, \tag{3}$$

here d_{max} is the distance between the most distant LEDs in a tile. For instance, for a tile with 32×16 LEDs placed at a 10 mm pitch, d_{max} is 320 mm and 160 mm in a horizontal direction and vertical direction respectively. If LED with $2\Theta_{0.5H} = 110°$ and $2\Theta_{0.5\ V} = 40°$ is used, this results in 108 mm r_{max} for a horizontal direction and in 206 mm for a vertical one.

Only variations introduced by a varying distance to a sensor and observation angle have to be corrected. Due to distance variations from a LED to sensor, the obtained measurement results have to be compensated for a distance induced irradiance change. Then the distance compensated irradiance is

$$I_{Dcomp} = \left(\frac{r}{r_{max}}\right)^2 I, \tag{4}$$

here r is a LED distance to the sensor, obtained as

$$r = \sqrt{(x - x_C)^2 + (y - y_C)^2 + r_{max}^2}, \tag{5}$$

with x and y being LED coordinates in a tile, x_C and y_C being the coordinates of the sensor position's right projection to the tile.

In conventional goniometry, a photosensor is always illuminated by a LED at the right angle. In the proposed measurement technique, a photosensor will be illuminated from different directions that will correspond to LED investigation angles. Therefore, the sensor directivity should also be taken into account. Sensor directivity can be measured as a function of horizontal Θ_H and vertical Θ_V angle, $S(\Theta_H, \Theta_V)$. This function can be used to compensate for sensor directivity influence.

$$I_{comp} = \frac{I_{Dcomp}}{S(\Theta_H, \Theta_V)}. \tag{6}$$

The obtained angular irradiance distribution can be regarded as an average FFP of the LEDs used in a tile. The problem is that the results will be corrupted by Θ_{peak}, I_{max}, $2\Theta_{0.5}$ variation of individual LEDs within a tile. Assuming this corruption as noise with normal distribution, this can be filtered through a least square function fit. This approximation function then could be regarded as a statistical LED FFP. It can be concluded that the average response of several LEDs now is replaced by an approximated FFP. Therefore, the final result will depend on the fact how accurate this function is following the average FFP of several LEDs. The investigation has been carried out for some approximation functions. By no means they are the final suggestions for use. One might be willing to use his own functions. The functions used just illustrate the ease of method application.

3.1. LED FFP approximation

FFP approximation is targeted on tinted LEDs. This type of LEDs is usually used in professional video screens. Therefore, the aim is to get a best fit of an approximated FFP to a goniometry measured pattern and to the measured average of FFPs as it is the raw data for screen directivity calculation. For this reason, only the functions giving the shape similar to the one of a LED FFP have been considered. Four simple functions have been considered as candidates for such approximation.

In luminous intensity measurements, a point light source usually is assumed. According to [3], angular intensity I distribution for point sources with rotational symmetry and various viewing angles can be approximated as:

$$I(\Theta) = I_{max}\cos(\Theta - \Theta_{peak})^{g-1}, \tag{7}$$

here I_{max} is LED peak luminous intensity at an angle normal to the source itself, whereas Θ_{peak} is the peak emission angle and g is a coefficient proportional to a viewing angle. Solution of Eq. (7) for $2\Theta_{0.5}$ leads to the following:

$$2\Theta_{0.5} = 2\arccos\left(e^{\left(\frac{\ln(2)}{g-1}\right)}\right). \tag{8}$$

Since tinted LEDs are assumed, tinting will affect a FFP. It could be expected that a single point light source assumption will no longer be valid. It would be useful to investigate other possible approximation functions. For the sake of computational efficiency, a second order polynomial fit can be used for FFP approximation. It should be noted that the shape of this function is not able to "bend back" as in the case at the lower part of a FFP. But it is effective in the upper region of a FFP. It is a parabolic function in the form

$$I(\Theta) = a_0 + a_1\Theta + a_2(\Theta)^2, \tag{9}$$

here a_0, a_1, a_2 are polynomial coefficients. A LED peak emission direction Θ_{peak} angle can be obtained under the condition of Eq. (9) derivative by Θ being equal to zero as

$$\Theta_{peak} = -\frac{a_1}{2a_2}\Theta, \tag{10}$$

Obtaining the equation for $I_v(\Theta_{max})$ and solving for half of it, the viewing angle is

$$2\Theta_{0.5} = -\frac{\sqrt{2a_1^2 - 8a_0a_2}}{2a_2}\Theta, \tag{11}$$

Gaussian approximation is used in RF antenna radiation pattern approximation as an idealized pattern if sidelobes can be disregarded.

$$I(\Theta) = I_{max}\cdot e^{\left(-\ln(2)\frac{(\Theta-\Theta_{peak})^2}{\Theta_{0.5}^2}\right)} = I_{max}\cdot 2^{\left(-\frac{(\Theta-\Theta_{peak})^2}{\Theta_{0.5}^2}\right)}, \tag{12}$$

If ambient light can not be completely removed during the measurement process, then the DC offset occurs. Gaussian with DC offset I_{Off} can handle such case.

$$I(\Theta) = I_{Off} + I_{max}\cdot e^{\left(-\ln(2)\frac{(\Theta-\Theta_{peak})^2}{\Theta_{0.5}^2}\right)} = I_{Off} + I_{max}\cdot 2^{\left(-\frac{(\Theta-\Theta_{peak})^2}{\Theta_{0.5}^2}\right)}, \tag{13}$$

Assuming that the FFP lower part is not converging towards zero, a DC component might be a part of a FFP. In this case, a viewing angle should be corrected as

$$2\Theta_{0.5C} = -\frac{2\Theta_{0.5}\sqrt{\ln(2) - \ln\left(\frac{I_{max}-I_{off}}{I_{max}}\right)}}{\sqrt{\ln(2)}}. \tag{14}$$

The L2-norm of the error between an original and fitted function has been considered as an approximation quality criterion

$$L2 = \frac{\sqrt{\int_{\Theta_1}^{\Theta_2}(I_o(\Theta) - I_a(\Theta))^2 dx}}{\sqrt{\int_{\Theta_1}^{\Theta_2}(I_o(\Theta))^2 dx}}\cdot 100\%, \tag{15}$$

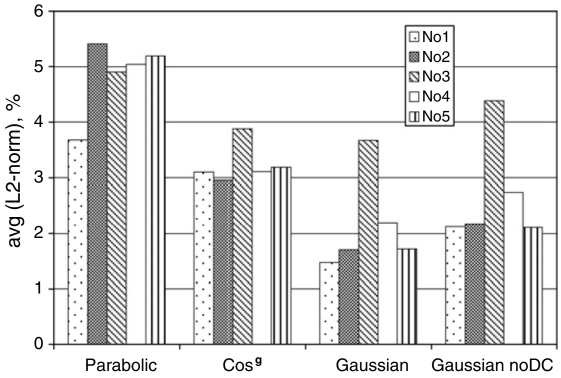

Fig. 5. Average approximation error L2 norm for various LEDs.

where I_o is an original FFP, I_a is an approximating function, and Θ_1, Θ_2 are the approximation range. The investigation result of batches of approximately 25 LEDs of various types from various manufacturers is presented in Fig. 5.

Investigated LEDs are representatives of the devices dedicated for high quality LED video screen imaging. They possess 110° viewing angle $2\Theta_{0.5}$ in a horizontal plane and have a relatively smooth FFP. Further analysis of approximation functions and performance evaluation criteria probably could reveal even better candidates. Increase of approximation function complexity would improve the approximation performance but result in higher sensitivity to noise. Outcomes for Gaussian approximation seem to be the most promising.

3.2. Measurement system

The system for LED directivity measurement in situ has been developed (refer to Fig. 6). From the explanation of LED goniometry presented in Fig. 1, system must contain a positioning device. The positioning device has been replaced by lighting a single LED in a tile, therefore, the desired inspection angle has been obtained.

TCS230 photosensor [7] from TAOS Inc. was used. All the communication with the host computer is accomplished using EZ-USB FX2LP IC CY7C68013A from the Cypress Semiconductor Corporation. USB2.0 transceiver, serial interface engine (SIE), enhanced 8051 microcontroller and a programmable peripheral interface are integrated in a single chip. The remote PC serves as a host and handles most of the measurement functions.

The measurement procedure is as follows:

1. LED tile is positioned in a measuring chamber and connected to a control unit.
2. Tile LEDs are lit in sequence and photosensor irradiance is recorded.
3. Irradiance data is corrected for distance and photodetector directivity.
4. The obtained data set is fitted with the desired FFP approximation function.
5. The obtained approximation is the representative of an average LED directivity FFP. If required, angles $2\Theta_{0.5}$, Θ_{peak} or resulting screen brightness $B_{SC}(\Theta)$ are calculated.

3.3. Sensor directivity

Sensor directivity has to be measured to compensate for different illumination angles. It was decided that for testing purposes it is sufficient for sensor

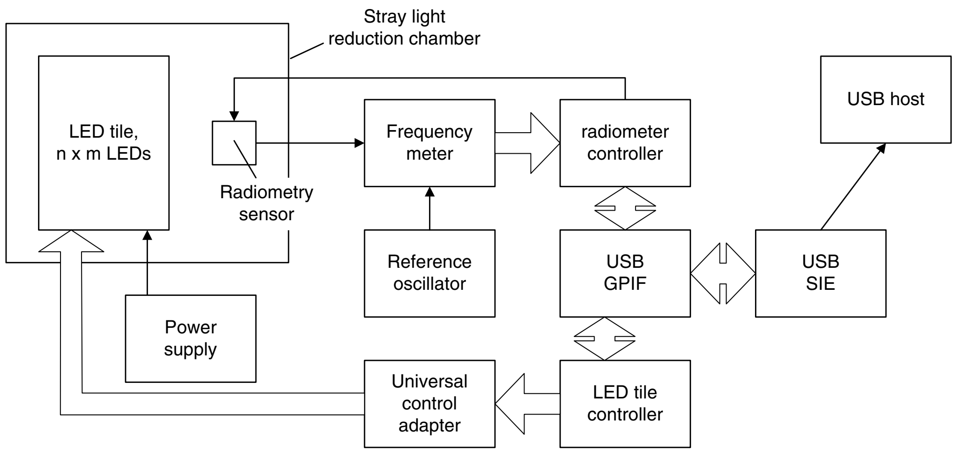

Fig. 6. Measurement system structure.

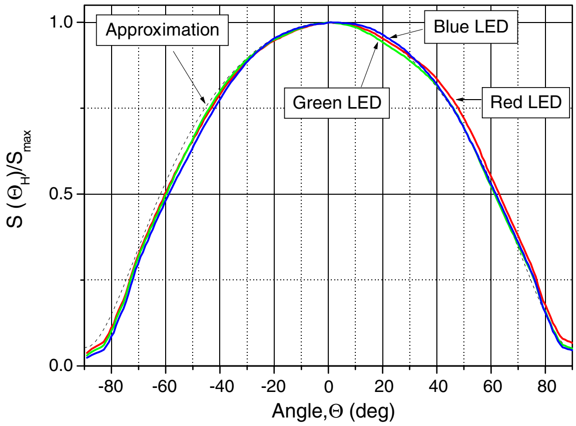

Fig. 7. Measured sensor directivity in a horizontal direction.

directivity to be measured as a function of horizontal $S(\Theta_H)$ and vertical $S(\Theta_V)$ angle. The resulting function $S(\Theta_H, \Theta_V)$ then is produced as the product of two

$$S(\Theta_H, \Theta_V) = S(\Theta_H) \cdot S(\Theta_V), \qquad (16)$$

Sensor directivity was measured using a LED goniometer [6]. The sensor was placed on an angle positioning unit and the LED has been attached into a photosensor place. The sensor was rotated and response was recorded in order to obtain the directivity response.

LEDs of three main colors have been used as the source. As Fig. 7 demonstrates, wavelength influence is insufficient. Therefore, it was decided to use the average results for polynomial approximation

$$S(\Theta_H) = a_0 + a_2(\Theta_H)^2 + a_4(\Theta_H)^4 + a_6(\Theta_H)^6, \qquad (17)$$

Only even order power was used to get a symmetrical response. For a vertical directivity, same type polynomial approximation was also considered as suitable. The obtained approximation functions have been used in further measurements.

4. Measurement results

For method performance evaluation, several sample tiles have been measured. in situ results have been obtained on a dozen of tiles from the same manufacturer. The LED tile had 32 LEDs in a horizontal direction and 16 LEDs in a vertical direction, totaling 512 LEDs. The LEDs were placed at a 10 mm pitch. One pixel is formed by one green, one blue and two red LEDs. This amounts to 6×8 pixels tile organization. A sensor has been placed at a 146 mm distance from the tile LED tip. This corresponds to a 106° and 66° maximal viewing angle in a horizontal and vertical direction respectively. A manufacturer has specified LED $2\Theta_{0.5}$ angle 110° in a horizontal direction, therefore, this setup is quite close to the thing which is needed. Then, by lighting the necessary single LED using the tile control interface sensor irradiation level was measured. The collected data $I_{c,r}$ was indexed for row (index r) and column (index c). After collecting radiometric data for the whole tile (Fig. 8), pixels have been split to form an array corresponding only to one color (Fig. 9).

The data has been processed for distance compensation using Eq. (4). After calculating the angle each individual LED has been measured at, data has been compensated for sensor directivity as per Eq. (6). Then data was copied into two arrays, i.e. horizontal and vertical. The horizontal direction array was regarded as a set of rows, normalized to its local peak. The vertical direction array was treated as a row set, normalized to its local peak. Then sets were averaged resulting in a single array for a

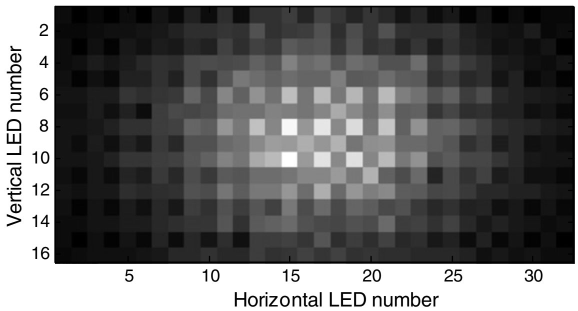

Fig. 8. Raw data of in situ measurement for a single tile, all LEDs.

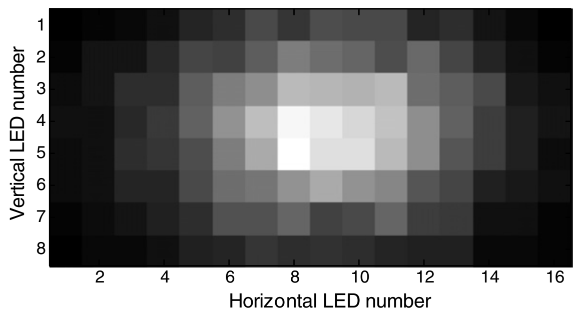

Fig. 9. Raw data, green LEDs only.

Table 1
Angle $2\Theta_{0.5}$ average for modules

LED	Approximation function			
	Parabolic	$\cos^{(g-1)}$	Gaussian	Gaussian0DC
	$2\Theta_{0.5P}$	$2\Theta_{0.5C}$	$2\Theta_{0.5G}$	$2\Theta_{0.5G0}$
Red	100.1	101.7	119. 7	103.9
Green	88.6	88.1	88.6	88.4
Blue	78.4	73.7	68.9	72.8

horizontal direction and a single array for a vertical direction. These arrays were used for least square fitting of an approximation function.

The approximation function was then applied to obtain $2\Theta_{0.5}$ angle for every tile. After processing of all the chosen tiles, results have been stored for further processing. The mean value of $2\Theta_{0.5}$ angle for red, green and blue LEDs based on these measurements is presented in Table 1.

4.1. LED goniometry results

In order to have some reference for the measurements, discrete LED measurements were required. For this purpose, a dozen of LEDs (20) has been desoldered from the tiles at randomly chosen locations. The removed LEDs have been placed in a goniometer and their FFP have been measured. The individual LED FFPs have been combined by averaging same color FFP according to Eq. (2). The obtained LED FFP has been used for $2\Theta_{0.5}$ angle measurement (noted as none in Table 2). Then, the FFP data has been interpolated applying the aforementioned approximation functions. The $2\Theta_{0.5}$ angles obtained from approximation are presented in Table 2.

5. Discussion of results

The simplest way would be to compare the $2\Theta_{0.5}$ angle values obtained by tile results approximation against the $2\Theta_{0.5}$ angles obtained from averaged

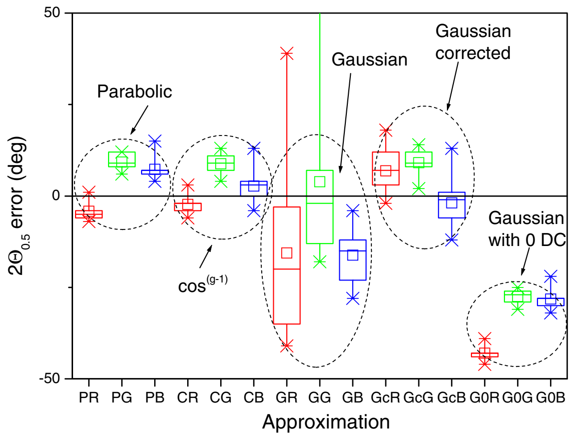

Fig. 10. Angle $2\Theta_{0.5}$ obtained by a module measurement approximation error.

FFP (noted as none in Table 2). Such comparison results are presented in Fig. 10. The error of the $2\Theta_{0.5}$ angle values obtained by tile results approximation is presented as a box-and-whisker plot. The box encloses 50% of data (the interquartile range, IQR)l; a line in the box represents the median; the mean is shown as a square. The whiskers are of 1.5 IQR and the stars represent the minima and maxima of data.

It seems that parabolic, cosine in power $g-1$ and corrected Gaussian function approximations have the best performance. A great scatter of results for Gaussian function can be explained by greater sensitivity to the lower intensity part where a signal-to-noise ratio is the worst. It would be interesting to eliminate the approximation influence by comparing both the module measurement and the goniometry approximation results for $2\Theta_{0.5}$. Results are presented in Table 3.

In this case, all functions have similar performance with a slight advantage of Gaussian with 0 DC.

The goal of this technique is to obtain the whole FFP. Therefore, the LED FFP approximation obtained by module measurement error L2 norm from the average LED FFP established by goni-

Table 2
Angle $2\Theta_{0.5}$ obtained by goniometry FFP approximation

LED	Approximation function					
	None	Parabolic	$\cos^{(g-1)}$	Gaussian	Gaussian corrected	Gaussian0DC
Red	105	113	109	89	106	63
Green	80	97	86	75	81	49
Blue	71	93	78	67	72	44

Table 3
Angle $2\Theta_{0.5}$ error degrees between the same approximations applied on an average LED FFP and modules average

LED	Approximation function				
	Parabolic	$\cos^{(g-1)}$	Gaussian	Gaussian corrected	Gaussian0DC
Red	−12	−6	0	6	−1
Green	−8	2	8	8	3
Blue	−14	−4	−12	−3	−1

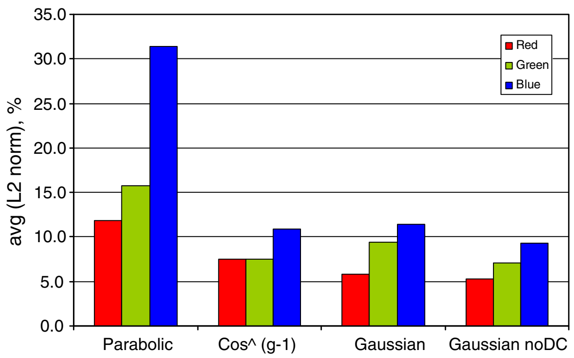

Fig. 11. Intensity approximation error average L2 norm for module measurements.

ometry was analyzed. Results are presented in Fig. 11.

It can be pointed out that the obtained tile approximation error L2 norm is similar to those of the LED FFP indicated in Fig. 5. As expected, variation in LED intensity and a peak emission direction has created more noise, which in turn has caused greater deviation of results.

Data presented in Fig. 12 serves for visual comparison of a LED average FFP and FFP obtained from tile measurements. The LED average FFPs obtained by averaging LED goniometry results are presented in Fig. 12 as thick lines.

For comparison purposes, raw data of tile No. 6 measurement is presented as a scatter graph (circles are for red,[1] triangles are for green and diamonds are for blue color). Gaussian approximation of raw data results is presented as dashed lines.

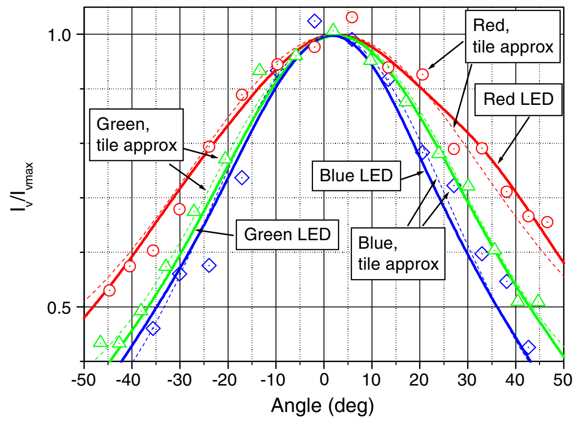

Fig. 12. Goniometry results (a thick line demonstrates goniometry results of free LEDs, whereas a dashed line demonstrates Gaussian approximation of tile measurement data).

6. Conclusions

The measurement technique suitable for LED directivity measurement in situ has been suggested. A LED FFP can be measured quickly without dismantling the LEDs from the tile. The obtainable accuracy and suitable approximation function analysis are beyond the scope of this paper. The brief analysis presented indicates that a cosine in power $g-1$ and Gaussian functions have a slight gain in performance. This technique should prove suitable when a fast and portable system is needed to evaluate or verify the LED tile directivity parameters.

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[1] For interpretation of color in Fig. 12, the reader is referred to the web version of this article.