IEC 60747-18-1

Edition 1.0 2019-05

INTERNATIONAL STANDARD

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Semiconductor devices –
Part 18-1: Semiconductor bio sensors – Test method and data analysis for calibration of lens-free CMOS photonic array sensors

IEC 60747-18-1:2019-05(en)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ICS 31.080.99

ISBN 978-2-8322-6909-1

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CONTENTS

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SEMICONDUCTOR DEVICES –

Part 18-1: Semiconductor bio sensors – Test method and data analysis for calibration of lens-free CMOS photonic array sensors

FOREWORD

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The text of this International Standard is based on the following documents:

FDIS	Report on voting
47E/643A/FDIS	47E/657/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the IEC 60747 series, published under the general title *Semiconductor devices*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

The IEC 60747-18 series on semiconductor bio sensors is expected to be composed of the following parts:

- IEC 60747-18-1 defines the test method and data analysis for calibration of lens-free CMOS photonic array sensor
- IEC 60747-18-2[1] defines the evaluation process of lens-free CMOS photonic array sensor package module
- IEC 60747-18-3[2] defines the fluid flow characteristics of lens-free CMOS photonic array sensor package module with fluidic system

The IEC 60747-18 series includes subjects such as noise analysis, long-term reliability tests, test methods for lens-free CMOS photonic array sensor package module under patchable environments, test methods under implantable environments, etc.

The International Electrotechnical Commission (IEC) draws attention to the fact that it is claimed that compliance with this document may involve the use of patents given in several subclauses as indicated in the table below. These patents are held by their respective inventors under license to SOL Inc.:

KR1020150081134	[SOL]	The method of calibration of photon sensor pixel array by evaluating its characteristic	Subclauses 5.1, 5.2.1, 5.2.2, 5.3, 7.1
PCT/KR2016/006109	[SOL]	METHOD FOR CORRECTING OPTICAL SENSOR ARRAY MODULE THROUGH CHARACTERISTIC EVALUATION	Subclauses 5.1, 5.2.1, 5.2.2, 5.3, 7.1 Clause 6
US15/577586			
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[1] Under preparation. Stage at the time of publication: IEC/PRVC 60747-18-2:2019.

[2] Under preparation. Stage at the time of publication: IEC/PRVC 60747-18-3:2019.

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SEMICONDUCTOR DEVICES –

Part 18-1: Semiconductor bio sensors – Test method and data analysis for calibration of lens-free CMOS photonic array sensors

1 Scope

This part of IEC 60747 specifies the test methods and data analysis for the calibration of lens-free CMOS photonic array sensors. This document includes the test conditions of each process, configuration of lens-free CMOS photonic array sensors, statistical analysis of test data, calibration for planarization and linearity, and test reports.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
lens-free CMOS photonic array sensor
semiconductor-based optical detector or sensor whose sensing elements are arrayed in a two-dimensional way and integrated with processing circuits on a chip

Note 1 to entry: Lens-free CMOS photonic array sensors are extensively utilized in bio diagnostic devices, healthcare devices, lens-free microscopes, and patchable/implantable medical devices.

Note 2 to entry: The sensing environments of such a lens-free CMOS photonic array sensor are typically different from those of general-purpose image sensors which are normally mounted with an external lens in module housings.

3.2
quantum efficiency
QE
ratio of the number of elementary events (such as release of an electron) contributing to the detector output, to the number of incident photons

Note 1 to entry: QE is the ability of a semiconductor to produce electron from incident photons.

Note 2 to entry: QE in general depends on the wavelength of the incident photon and can be obtained from spectral responsivity and conversion gain of the sensor.

[SOURCE: IEC 60050-845:1987, 845-05-67, modified – The abbreviated term and the notes to entry have been added.]

3.3
linearity
ability of a pixel of an array sensor to provide an output having a linear relationship with an input light power

3.4
box plot
graphically depicting group of numerical data through their quartiles Q1, Q2, and Q3

SEE: Figure 1.

Note 1 to entry: In this document, the noise RMS (root mean square) and average signal are added. The average signal is different from the median value, which is real measured data, whereas the average is calculated. Noise RMS is the root mean square value of the difference between the incident signal and average signal.

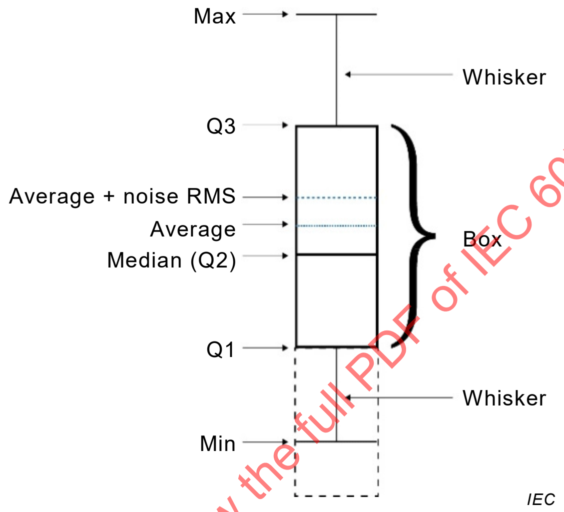

Figure 1 – Example of box plot

4 Measurement setup

4.1 General

Input factors and environmental factors affecting sensor performance are: (1) input component: light power (wavelength, intensity, incident angle, polarization) and its two-dimensional distribution as well as stability over time; electric inputs (drive pulses, bias voltages, etc.); and (2) environmental factor: temperature. The evaluation environment provides a method that allows us to control these factors and to obtain numerical results with the necessary accuracy. The performance of the lens-free CMOS photonic array sensor depends on the resolution, pixel size, pixel type, fill factor, quantum efficiency, conversion gain, sensitivity, saturation level, dynamic range, image lag, black level, dark signal, temporal noise, fixed-pattern noise, cross talk, etc. Clause A.1 and Clause A.2 show the required parameters.

4.2 Measurement system

4.2.1 Overall system

All tests shall be performed under well certified and defined conditions to avoid any external disturbances. Basic measurement setup schematics are depicted in Figure 2 or Figure 3.

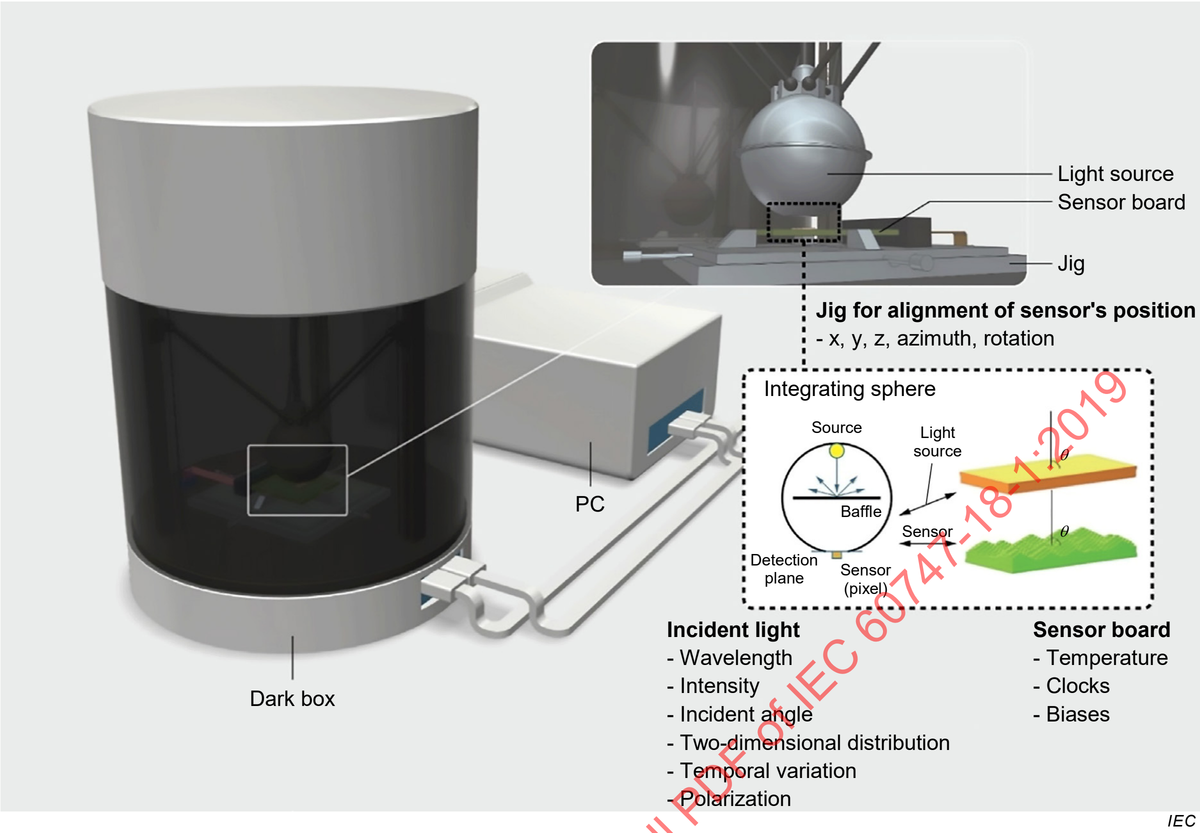

Figure 2 – Example of measurement system with integrating sphere

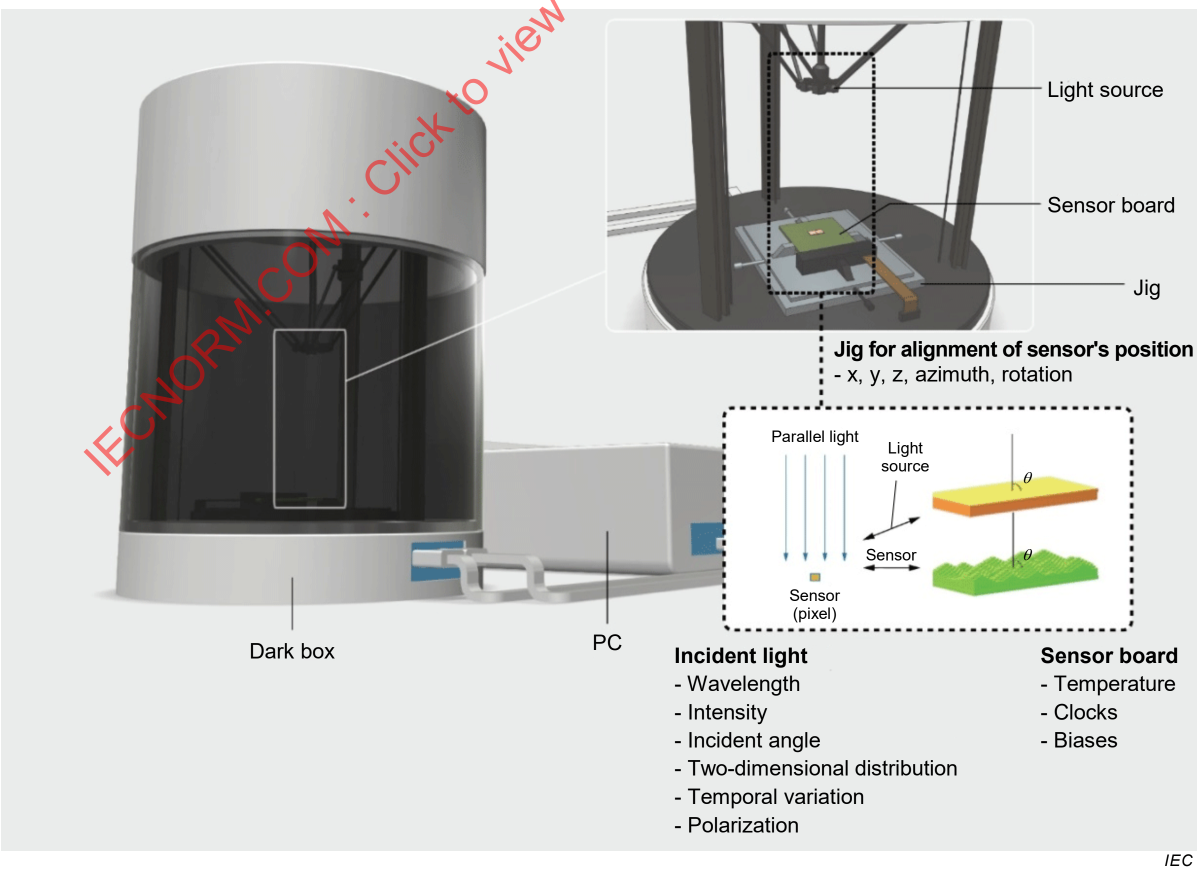

Figure 3 – Example of measurement system with incident parallel light

The photoelectric characteristics of a sensor board can be measured using the measurement setup shown in Figure 4. This measurement setup utilizes a collimated light beam. The temperature of the sensor array is measured to calibrate the thermal effect on the array sensor. A calibrated photonic sensor will be used to provide a reference signal for the collimated light.

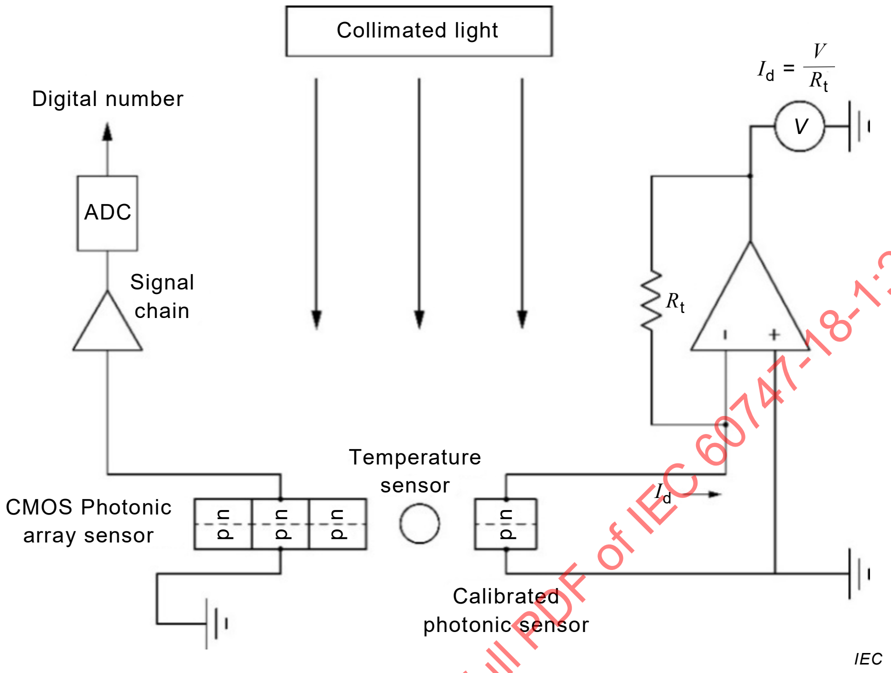

Figure 4 – Example of photoelectric measurement schematic

4.2.2 Dark box

A dark box shall block all other light sources that may affect the sensor under test except the certified light source for test.

4.2.3 Light source

All the light source characteristics listed below shall be specified:

– spectral characteristics of peak wavelength and spectral bandwidth for monochromatic light; correlated colour temperature for white light;
– total radiant power and angular distribution of output beam;
– incident angle of light: default condition is perpendicular to the sensor surface;
– spatial uniformity of power in the area of the detector under test (non-uniformity shall be less than the resolution limit of digital number output);
– temporal stability;
– polarization: un-polarized.

4.2.4 Sensor board

All the properties of photonic sensor board listed below shall be specified or defined:

– temperature;
– clocks;
– biases;
– characteristics of the light absorption film or anti-reflection coating film to block second light sources from the original light, if applied;

– frame capture interval of the frame capture board.

4.2.5 Configuration parameters

The configuration parameters listed below shall be specified:

– integration time;
– analogue gain;
– digital gain;
– frame rate.

NOTE 1 The integration time is usually set to multiples of flicker period under half of saturation light.

NOTE 2 The analogue gain for a value is related with noise (or measurement error).

5 Measurement

5.1 General

Each pixel of the CMOS photonic array sensor experiences noise from multiple noise sources and there are responsivity variations between pixels in the array sensor. Therefore, multiple measurements with the same input and environment factors should be made and these should be statistically processed in order to cope with such noise and spatial variations in responsivity. For the linearity test, light intensities or integration time may be the variables. All the measurements can be done with different light sources (wavelengths). Measurement flow may be carried out in accordance with Figure 5.

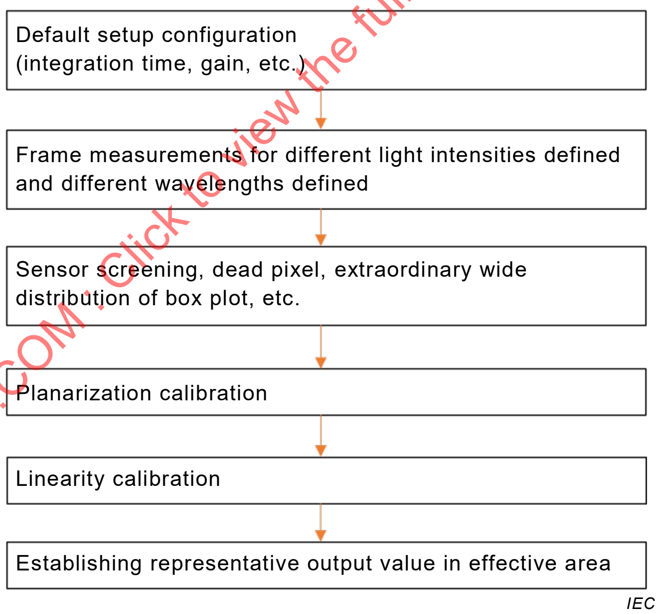

Figure 5 – Measurement flow

5.2 Case 1: Fixed wavelength (λ) of light

5.2.1 Planarization: At fixed λ and incident light intensity

5.2.1.1 General

At a fixed wavelength and light intensity, the frame measurement shall be carried out according to the three sequential steps described in 5.2.1.2 to 5.2.1.4.

5.2.1.2 Step 1: n trial of frame capture

The data of a single frame is measured and the same measurement is repeated n times to get the statistics of the frame shown in Figure 6.

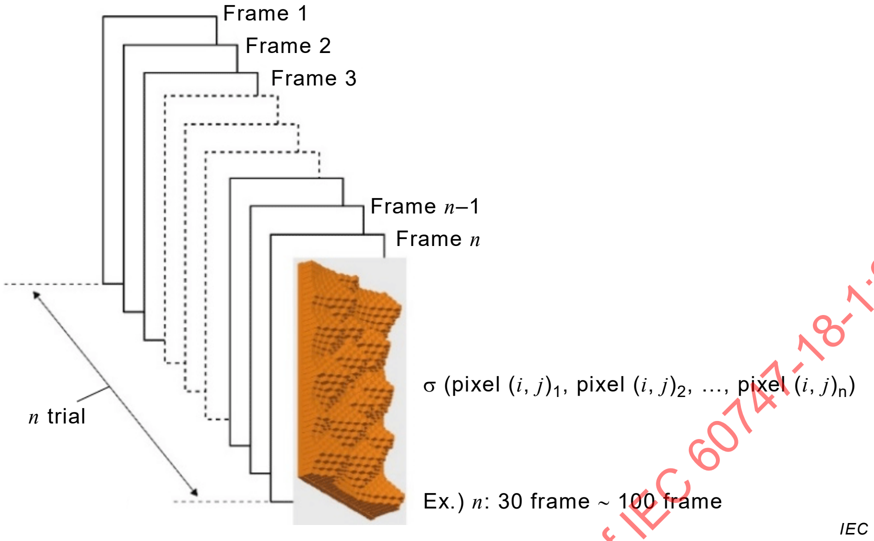

Figure 6 – n trial data of frame capture

5.2.1.3 Step 2: Subtraction of the two continual frame data

As shown in Figure 7, the differences between the current frame data and the previous frame data are collected and the differences between the data and delta are stored to get the statistics (the data reduction) for extracting random signals, excluding fixed signals, especially fixed pattern noise.

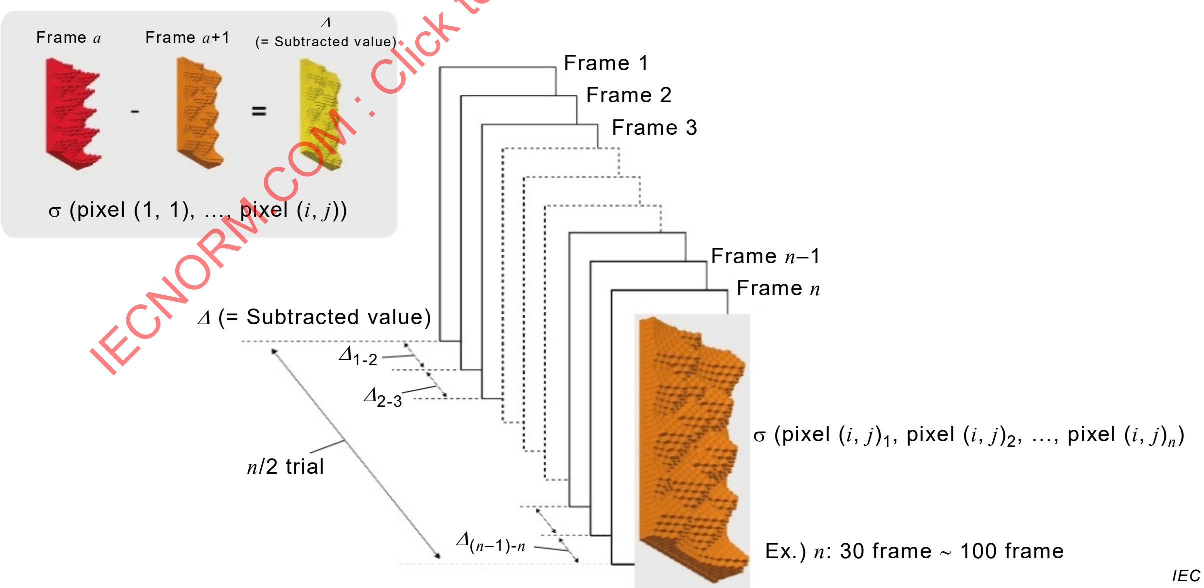

Figure 7 – Two frame subtracted data

5.2.1.4 Step 3: Subtraction of dark frame data (dark offset calibrated data)

As shown in Figure 8, the dark frame data without illumination and the frame data with light are measured to remove the dark (offset) noise and these data are stored to collect statistical information on the illuminated response or photon response of each pixel.

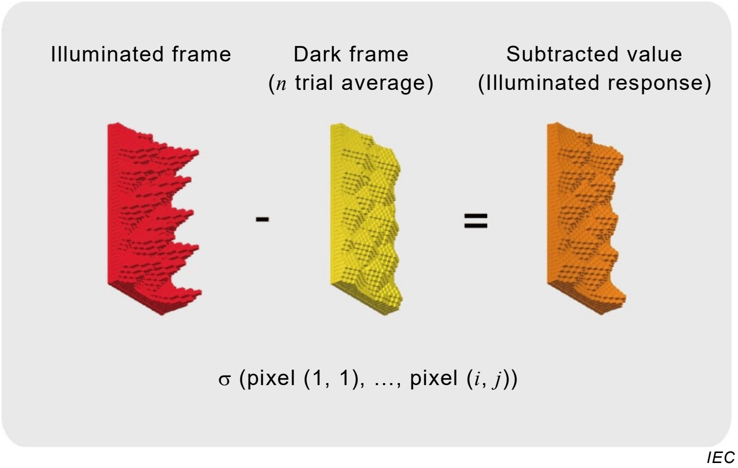

Figure 8 – Dark frame subtracted data

5.2.2 Linearity: Varying the incident light intensity with a fixed wavelength

The measurement explained in 5.2.1 shall be repeated by varying the incident light amount while the wavelength (λ) and the integration time are fixed.

Alternatively, the measurement explained in 5.2.1 shall be repeated by varying the integration time while the wavelength and the incident light intensity are fixed. Varying the integration time has the benefit of exact time control according to the clock at a cost of increased dark noise. The incremental step of the input light intensity is possibly smaller than the minimum incremental unit of the output signal in order to obtain more precise measurement values.

5.3 Case 2: Various wavelength (λ) of light

The measurement explained in 5.2.1 and 5.2.2 shall be repeated by varying the wavelength of incident light.

6 Data analysis

6.1 Data plot

6.1.1 General

In general, not every pixel array shows the same output value when exposed to light with the same intensity. Moreover, the output value (of the pixel) does not change linearly in accordance with increasing light intensity. The statistical distribution of the 3D output data of all the pixels shall be informed by using box plots. Figure 9 shows pictures of 3D data illustrating the photon transfer non-linearity phenomena of the 2D pixel array depending on three different light intensities.

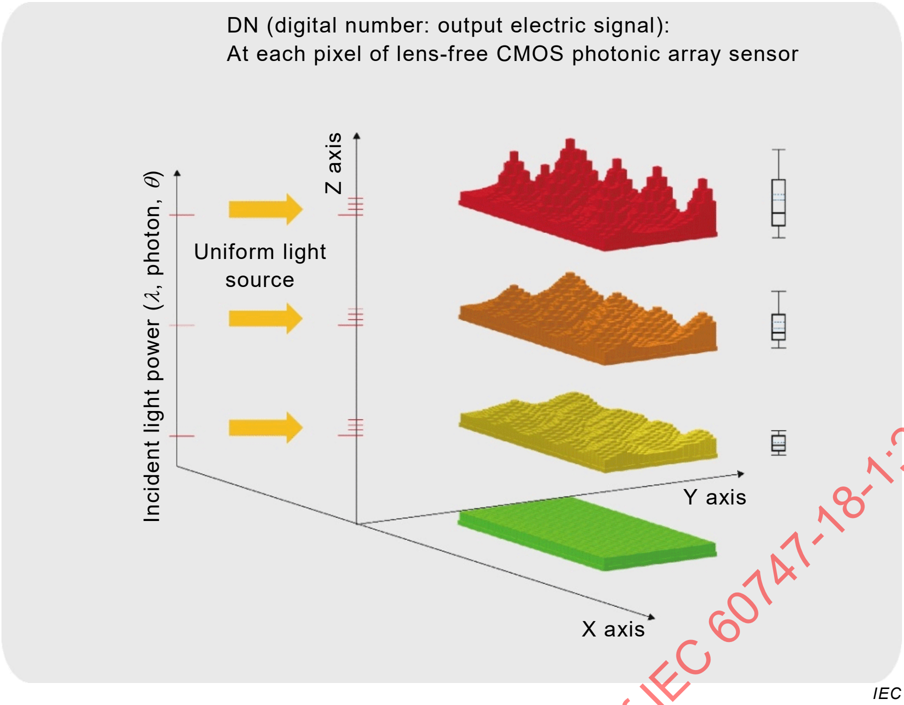

Figure 9 – Example of output electric signal non-linearity of 2D pixel array

Box plots shall be drawn for all the pixels in a row using representative values (average, mean, etc.) at a specific light intensity so that the distribution thereof is known.

Figure 10 shows an example of the output electric signal characteristic of a typical row of pixels, with the statistics (minimum, maximum, median, average, RMS, standard deviation) of each pixel.

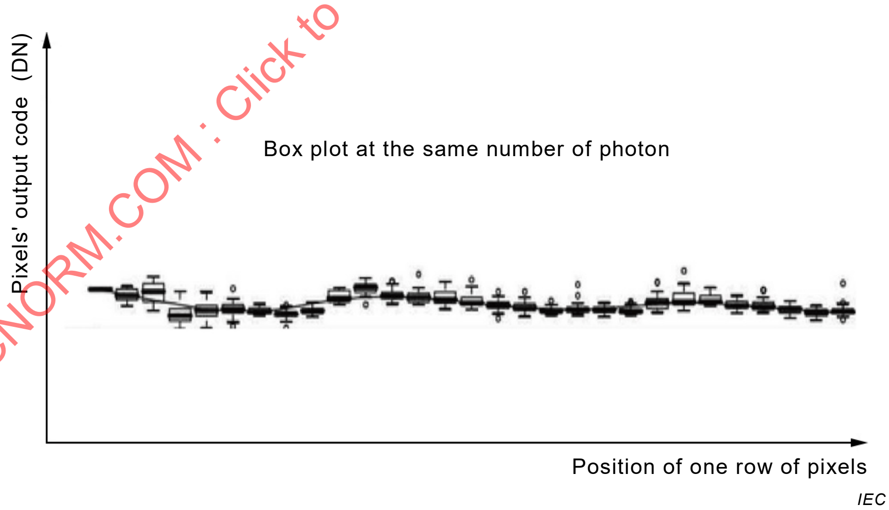

Figure 10 – Example of output electric signal non-linearity of one row of pixels

Also, the user should be able to see the distributional deviation of the output of n trial by plotting the output value of the light intensity of the pixel showing the representative value thereof, and drawing the box plot for each intensity. Figure 11 shows the highlights of photoelectric characteristic data which depict the relationship between light intensities and the output response of a typical pixel. Saturation level, dark level, noise floor, linearity, responsivity and measurement error distribution can be deduced from this data.

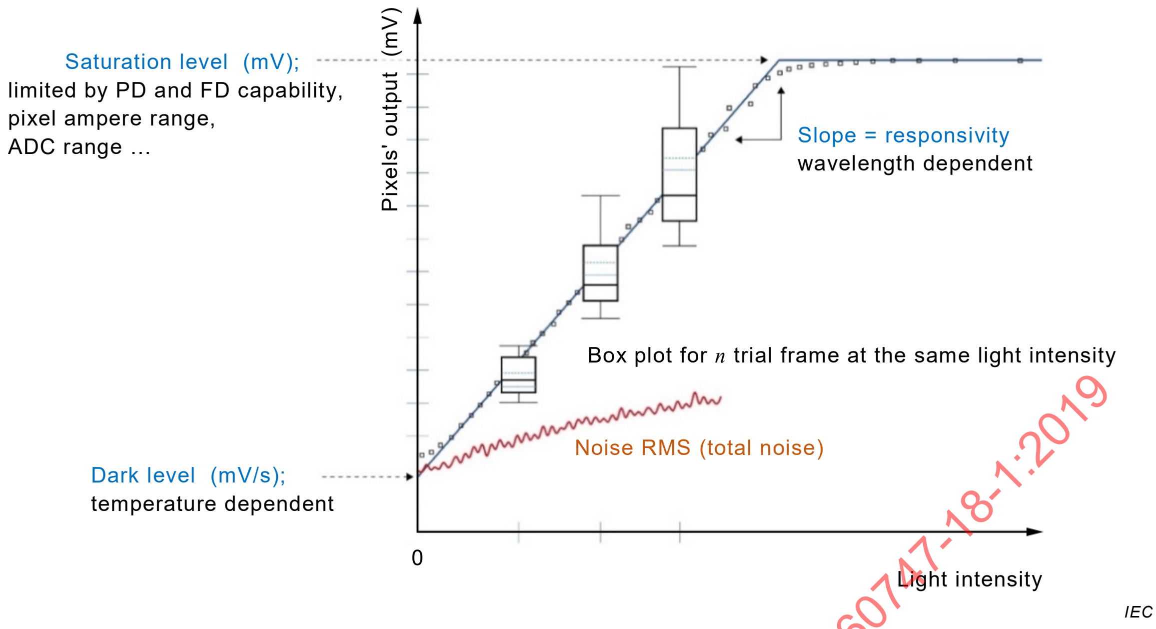

Figure 11 – Example of one pixel's output electric signal according to input light power

6.1.2 Sensor screening

Sensors that require measurement accuracy and reliability shall be selected in advance. According to the measurement result of the sensors, it is desirable to exclude a sensor wherein a dead pixel is found, or where the distance between the minimum and the maximum points of the box plot are too wide, or the length of the box is too long, or the linearity is not so good. It is recommended that the sensor screening guidelines on this matter be set out in the data sheet.

6.2 Planarization characteristics

6.2.1 Criterion of determining the reference pixel

Planarization reference pixels for calibration are the pixels with the minimum distribution value in terms of n measurements. For example, as shown in Figure 12, the planarization reference pixel could be the pixel with the smallest value of Q3 – Q1 in X number of pixels whose Max – Min values are lower 1 % of values in pixels after n measurements.

See also Figure 1 and 3.4 for Q1, Q3, Max, and Min.

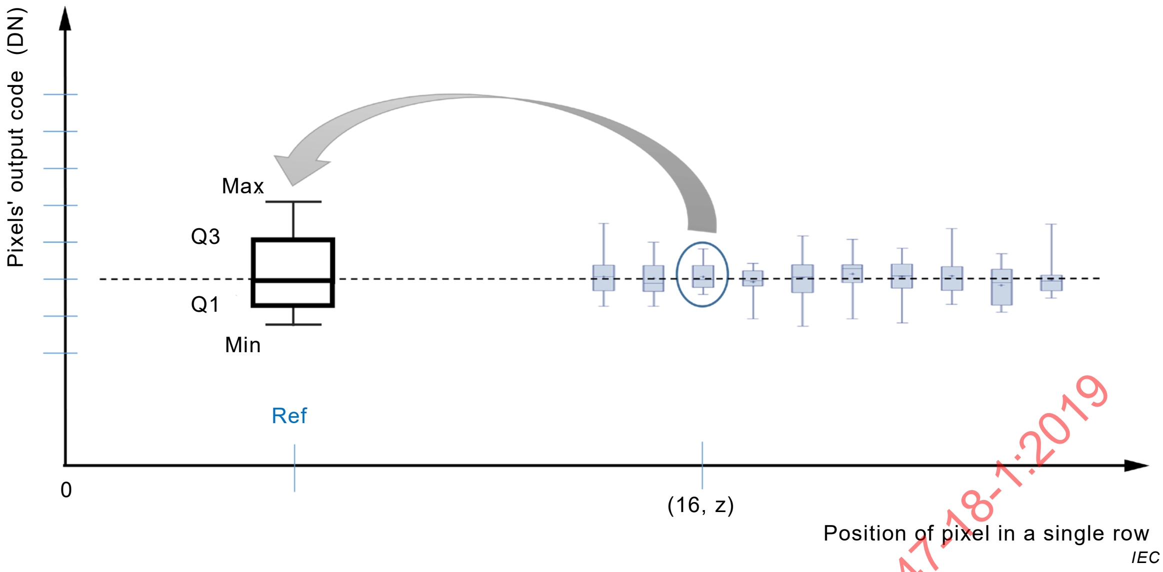

Figure 12 – Example of determining the reference pixel

6.2.2 Lookup table of representative value for planarization calibration of each pixel

The representative value of each pixel for planarization calibration shall be determined by one of mean, median, and mode of each pixel, as in Figure 13. For example, each representative value can be determined by taking the mean of the first pixel, mode of the second pixel, and median of the third pixel. (It can be decided after considering the co-relationship between each pixel's prospective characteristics (such as optical, electrical, and structural characteristics due to the process conditions of each manufacturer) and the statistical distribution of measurement data.) After determining the representative value of each pixel, the matrix of the representative value corresponding to each pixel is generated. The lookup table for the planarization calibration of each pixel is completed with the variable or function which adjusts the representative value of each pixel in the matrix to the representative value of the reference pixel. The lookup table of the representative value for planarization calibration (Lookup table_RVP) of each pixel shall be written in a test report.

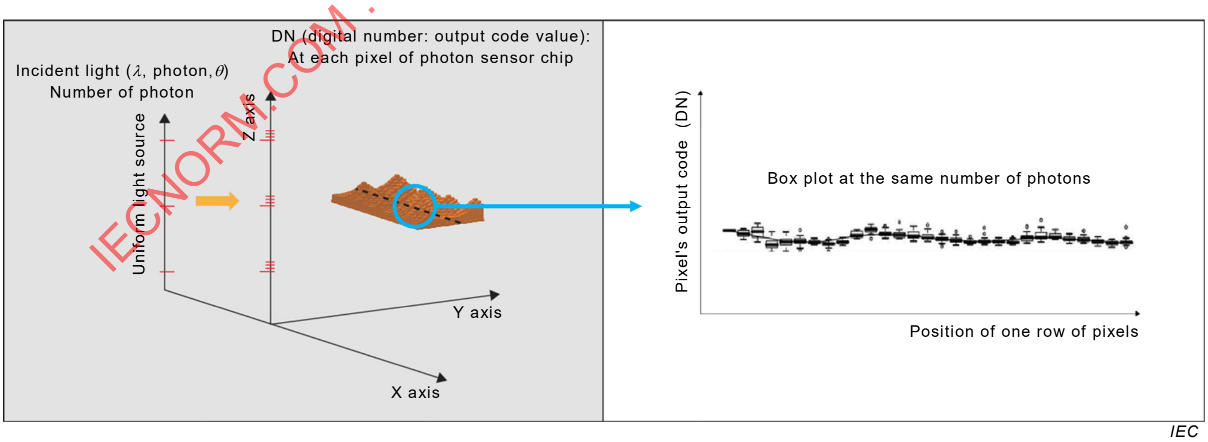

Figure 13 – Example of the representative value for planarization

6.3 Linearity

6.3.1 Criterion of linear region of each pixel

The linear region of each pixel shall be set up within the region of light intensity in which the output code increases linearly with the increase in light intensity. The linear region of the reference pixel, regression equation, and coefficient of determination (such as R-square, adjusted R-square, etc.) shall be provided by supplier. The regression equation and coefficient of determination of reference pixels shall be written in the test report. Linear regions of other pixels are obtained from the regression equation, which has a higher value than that of the coefficient of determination of the reference pixels.

6.3.2 Criterion of light intensity effective area for linearity

The light intensity effective area for the linearity of the CMOS photonic array sensor shall be the intersectional region of all pixels' linear regions. For example, as shown in Figure 14, the light intensity effective area of all pixels can be specified from b0 to a1. The linear region of pixels A, B and C are from a0 to a1; from b0 to b1; and from c0 to c1, respectively. The light intensity effective area for linearity shall be written in the test report.

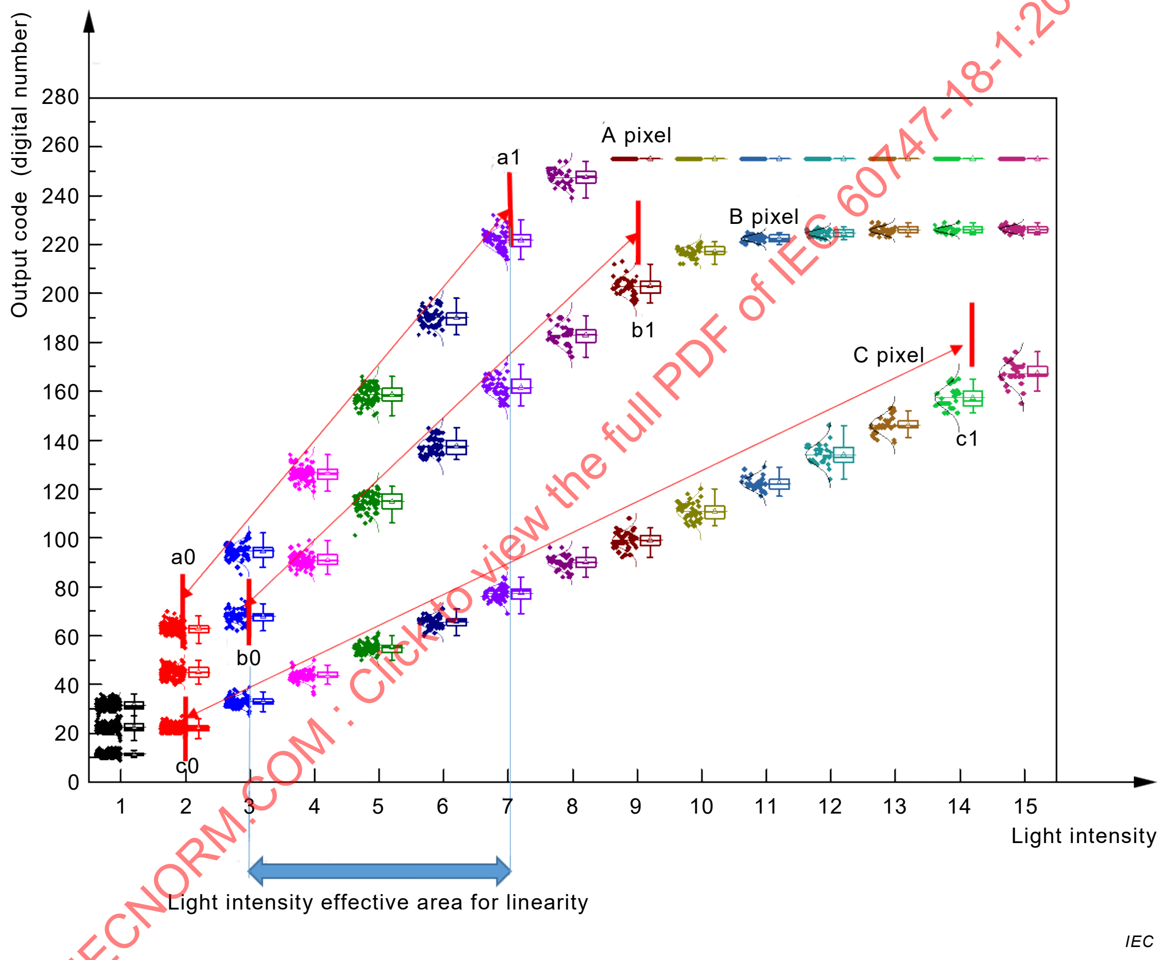

Figure 14 – Example of light intensity effective area for linearity

6.3.3 Lookup table of the representative value for linearity calibration of each pixel

The representative value of each pixel for linearity calibration shall be determined by the mean, median and mode of each pixel, as shown in Figure 15. For example, as for the representative value of each pixel for linearity calibration, each representative value can be determined by taking the mean of the first pixel, mode of the second pixel, and median of the third pixel. (It can be decided after considering the co-relationship between each pixel's prospective characteristics (such as optical, electrical, and structural characteristics due to the process conditions of each manufacturer) and the statistical distribution of measurement data.) After determining the representative value of each pixel, the matrix of the representative value corresponding to each pixel is generated. The lookup table of representative values for the linearity calibration of each pixel with various incident light intensities is completed with the variable or function which adjusts the representative value of each pixel in the matrix to the representative value of the reference pixel. The lookup table of the representative value for linearity calibration (Lookup table_RVL) of each pixel shall be written in the test report.

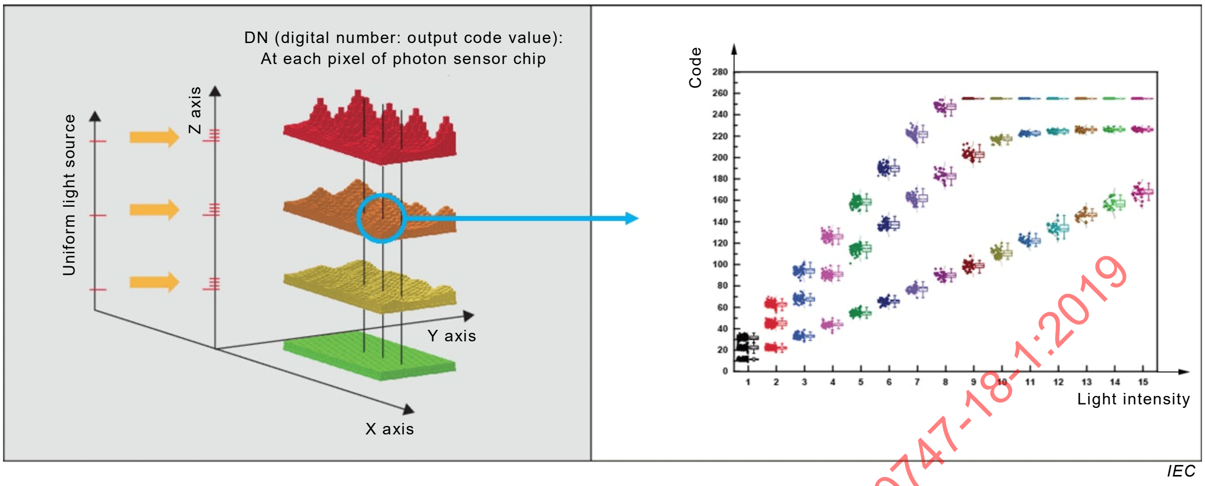

Figure 15 – Example of the representative value for linearity

7 Calibration

7.1 Calibration lookup table

There may be a structural difference or a difference in the features of the sensors used for each product. Figure 16 shows a simplified pixel cross section to explain how the surface planarization and the properties of the raw materials (filter, dielectric, microlens, etc.) in the sensor array affect the photoelectric characteristics during light penetration to the photonic sensor.

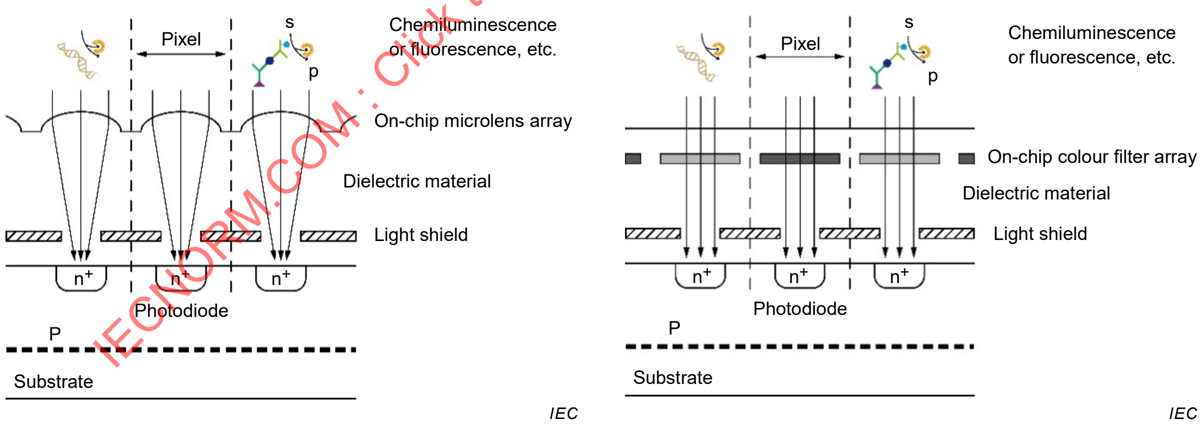

Figure 16 – Example of a simplified pixel structure and cross-sectional view with bio reaction

Calibrations are required for a correct measurement to avoid errors due to the pixel variations of an array sensor and output nonlinearity dependence on the light intensities. A calibration lookup table for the pixel array shall be formed as set out in Table 1. The calibration lookup table (Lookup table_CAL) shall be included in the test report.

Table 1 – Calibration lookup table

Incident light intensity	Target calibrated output value (digital number: light intensity)	Measured output electric signal	Planarization calibration coefficient	Linearity calibration coefficient
I_1	1: aaa	$\text{OES}_{\text{measure\_1}}(x_i, y_j)$	$\text{PCC}_1(x_i, y_j)$	$\text{LCC}_1(x_i, y_j)$
~	a~	~	~	~
I_{zzz}	Maximum digital number: zzz	$\text{OES}_{\text{measure\_max}}(x_i, y_j)$	$\text{PCC}_{\text{Max.}}(x_i, y_j)$	$\text{LCC}_{\text{Max.}}(x_i, y_j)$

– (x_i, y_j) is a pixel at the position $_{i,j}$.

– OES is an output electric signal value.

– $\text{OES}_{\text{measure\_zz}}(x_i, y_j)$ is a measured output electric signal value of pixel at the position $_{i,j}$.

– $\text{PCC}(x_i, y_j)$ is a planarization calibration coefficient of pixel at the position i,j for the geometric and physical difference of passivation layer, micro-lens, colour filter etc.

– $\text{LCC}(x_i, y_j)$ is a linearity calibration coefficient of pixel at the position $_{i,j}$ for the non-linearity of each pixel.

NOTE OES can be presented either in voltage or Digital number (DN).For example, for an 8-bit ADC, the DN is from 0 to 255 while for a 10-bit ADC, the DN is from 0 to 1 023.

7.2 Reference for establishing the representative output value in the effective area

The statistical distribution of the output code is measured by adjusting light intensity continuously or discretely n times within the effective area for linearity, as in Figure 17. The difference of each statistical distribution of output codes at two adjacent light intensities shall be greater than or equal to zero. Suppliers shall determine how to divide the difference and include it in the statistical distribution of higher output codes or lower output codes according to its own policy or algorithm. For example, if there are two non-occupied digital numbers between two adjacent statistical distributions of output code, suppliers can divide the two digital numbers into two parts to disperse each one into two statistical distribution groups of output codes, or include the two digital numbers into one distribution group only. Generally, the supplier can find the code-variation function from the experimental data to get the pixel output range and its representative value. Pixel output range comprises the statistical distribution of output codes and the difference of each statistical distribution of output codes. Finally, the representative value of the sensor corresponding to each pixel output range is obtained. A representative value table of the sensor shall be included in the test report, as shown in Table 2.

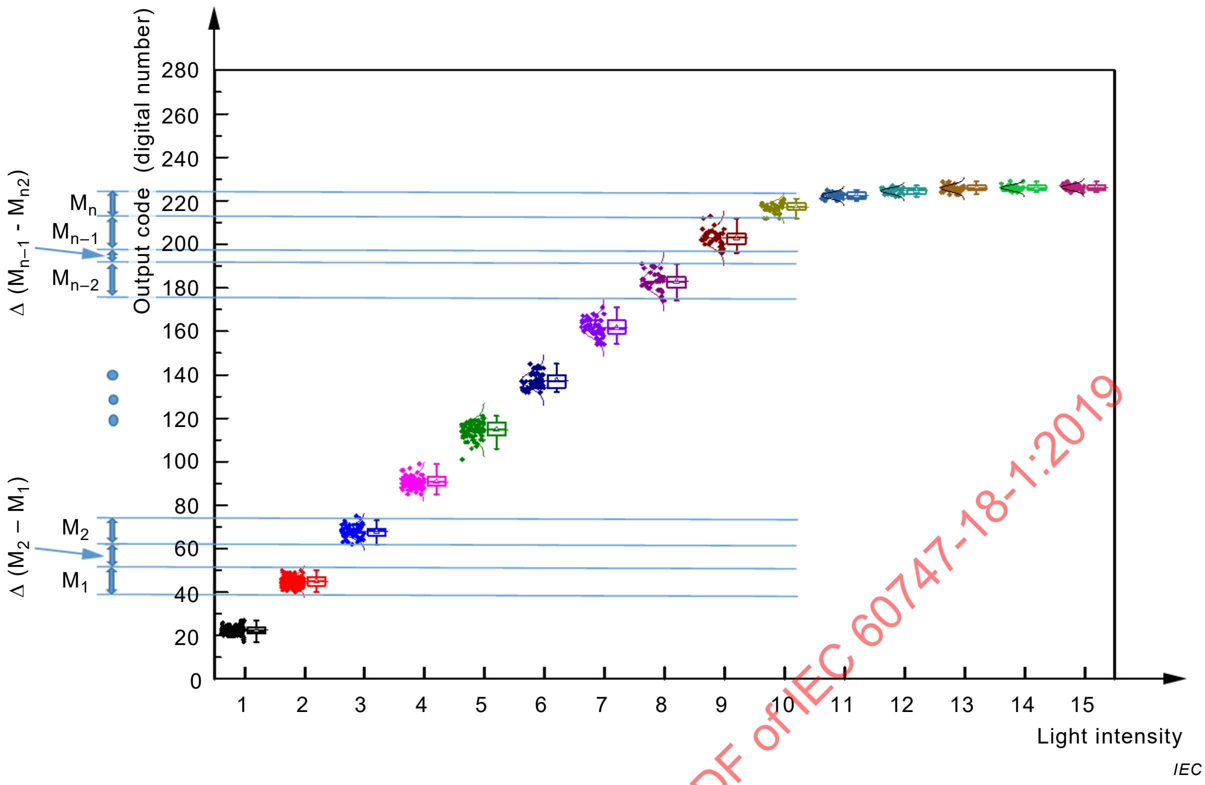

Figure 17 – Example of the representative value of the sensor

Table 2 – Representative value table of the sensor

Incident light intensity	Statistical distribution of output codes	Pixel output range (digital number)	Representative value of the sensor
I_1	1 to 28	1 to 29	Non-effective area
I_2	30 to 36	30 to 37	M_1
I_3	39 to 46	38 to 47	M_2
I_j	101 to 109	100 to 110	M_{50}
$I_{n\text{-}1}$	226 to 234	225 to 235	M_{100}
I_n	237 to 254	236 to 255	Non-effective area

8 Test report

The test report shall include the following information. An example of test report is in Annex A.

a) Test environment specification:
   - standard dark box;
   - light source setup:
   - sensor board:
   - configuration of parameters.

b) Specification of the lens-free CMOS photonic array sensor.

c) Specification of calibration:
   - regression equation and coefficient of determination of reference pixel;
   - light intensity effective area for linearity;
   - lookup table of representative value for planarization calibration (Lookup table_RVP);
   - lookup table of representative value for linearity calibration (Lookup table_RVL);
   - calibration lookup table (Lookup table_CAL);
   - representative value table of the sensor.