Spatial Characterization of LED's Irradiance using Ordinary Detectors

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Abstract

In this article, irradiance profiles of common LEDs along the beam propagation direction and in a plane perpendicular to propagation direction are studied using inexpensive photo detectors, viz., photo diode and photo transistor. Different methods used in Indian institutes for the analysis of radiation are discussed along with their limitations and advantages. General considerations required to characterize anisotropic radiators using ordinary detectors are discussed. It is found that, out of the two detectors photo transistor works better for LEDs radiations. These results are compared with results obtained from another anisotropic radiator, viz., open laser diode and one isotropic radiator incandescent lamp.

1 Introduction

Irradiance from a point source varies in a predictable way as a function of distance and angle. i.e., such radiation is isotropic and their irradiance describe inverse square law in all directions [1]. Actual nature of irradiance from any given source can be determined with the help of a well calibrated detector [2]. On the other hand, a source that describes standard radiation behaviour can be used to test the performance of a given detector. Often, low cost detectors and radiation sources that are available in the market fail to satisfy standardization tests. If a system of an uncalibrated detector and an uncalibrated source is provided, then its working status needs to be tested before using it for any further studies. This article attempts to address precisely this difficulty faced by the people who use such systems. Working of such a system is examined by the study of source' irradiance from a given detector as a function of separation distance between them by three methods. In addtion, this paper attempts to compare these methods and attempts to rectify the limitations of such measuring systems.

Most commonly available LEDs are used here and they are normally anisotropic radiators. While a small part of radiation is emitted by an LED in a hemispherical shape, a large amount of its radiation is emitted in a direction perpendicular to the emitting surface. However, even such radiation beam from LED is not unidirectional, instead it diverges from the exit end of LED. Encapsulation of LED provides certain radiation pattern by acting as a lens and it also provides mechanical protection to LED [2]. The typical Lambertian radiation pattern from an ordinary encapsulated LED shows that light energy is generally emitted in an angular range between 4° to 160° from the direction of maximum light for various encapsulations [2, 3, 4]. Not limitting to this angular range, there are special LEDs with wide angle of emission extending up to nearly 360° [5]. In order to understand the irradiance nature from a particular LED, it is necessary to have the knowledge of irradiance profile of that LED in all spatial directions [2].

Irradiance of LED along its propagation direction is expected to describe some power law with distance. A few reports of optical power law measurements using LEDs as radiation sources are available. Rajesh *et al* have used common LED as source and a photo diode as detector, but they have only plotted $(1/i_o)^{1/2}$ versus d, without reporting the exponent of distance with radiation [6]. Kutzner *et al* used common LED as source and another LED as a photo detector and obtained an average exponent of -2.23 [7]. Wanser *et al* have used light (intensity) to frequency converters as detectors and two different types of special LEDs for their study and obtained an exponent of ≈ -2.00 with high accuracy data [5]. Note here that, these two are special LEDs designed for special applications and they are different from the LEDs which are characterized by nearly unidirectional emission pattern. The latter type of LEDs are used in this work. In addition, inexpensive and uncalibrated photodiode and phototransistor are used here as detectors so that this experiment can be implemented with a modest budget in any undergraduate institutions.

2 Theory

A light detector always measures irradiance of source and its output current i_o is linearly proportional to the amount of irradiance E sensed by it [8].

$$\texttt{i.e.,}\ i_o \propto E \tag{1}$$

The irradiance E is a measure of the concentration of the optical power. It is defined as radiant flux (power) received by the unit area of the irradiated surface of the detector [1]. Radiant intensity I is the radiant flux emitted per unit solid angle. Given a point light source, for normal incidence, the irradiance E, Radiant intensity I and separation distance d are related through the relation [1, 9].

$$E = I/d^2 \qquad (2)$$

A plot of E versus $1/d^2$ should give a straight line with I as its slope. The objective of this method is to observe, how best the data fit into a straight line. A reasonably good conformity to the plotted data corroborates inverse square law.

Equation (2) is true for radiations from an isotropic radiator like a point source. At this point, a question arises; does radiation from an anisotropic radiator like LED follow (2) or not? If not, how its irradiance is related with d? These are addressed below.

Let 'n' be the exponent of distance between detector and source, such that,

$$E \propto 1/d^n \implies E = k'/d^n \qquad (3)$$

Where 'k'' is the proportionality constant. Taking log on both sides of (3),

$$\log E = \log k' - n \log d \qquad (4)$$

It is clear from (4) that, a plot of $\log E$ versus $\log d$ should yield a straight line with the true power index 'n', as its slope.

In this article, i_o is used instead of E, according to (1). If there is any factor between i_o and E, then it is expected to merge with the proportionality constant k' through the relations, (1) and (3) to a new constant k. Then k is directly related to radiant intensity I and the relation (4) modifies to,

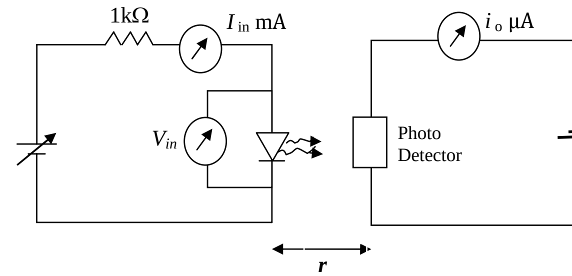

Figure 1: Circuit connections for the investigation of LEDs radiation.

$$\log i_o = \log k - n \log d \qquad (5)$$

It is clear from (5) that using i_o instead of E, does not affect the estimation of n in any manner. More rigorous approach to know the true power law of radiation was developed from a two aperture approximation model for LEDs radiation and a modified inverse square law was used to obtain more consistent results [2, 10].

3 Description of the Setup

The circuit connections are made as shown in figure 1. Mounted LED and detectors are placed on a graduated optical rail, which helps in their alignment and also in smooth variation of the distance between them. A photo detector mounted on a XYZ translation stage with micrometers of LC 10 μm

(=0.01 mm) is used to scan the LED's radiation beam. Here blue and red LEDs are used for characterization. To study the LED's radiation pattern in three dimensions, two different types of detectors are used, viz., a reverse biased (-5 V) silicon photo diode (part # PD-M-LK2-SHARP BS520) and a collector emitter reverse biased (-5 V) silicon based photo transistor (part # PT-M-LK-EVERLIGHT PT 333-3C) [11]. Photo transistor is enclosed in a pinhole chamber to avoid the effect of ambient radiation on the measurement. While using photo diode proper care has been taken to reduce the effect of ambient light on the measurements. The size $2R'$ (R'-radius) of the pin hole aperture in front of the photo transistor is ≈ 0.7 mm and therefore the exposed area A of the photo transistor is $\pi(R')^2 = 0.385$ mm^2 [11]. Active area A of the photo diode is 5.32 mm^2 [11]. LEDs, photo detectors and all opto-mechanical equipment are from Holmarc, India.

In addition to anisotropic LED sources, another anisotropic radiator viz., a laser diode without collimating lens (Holmarc, 3 mW, 650 nm) and an isotropic radiator, 100 W incandescent bulb are used in the study. A typical laser diode output beam is highly diverging with a large divergence angle ($\theta_\perp$, full width at 50 % intensity) in the direction perpendicular to the rectangular junction of diode, and it diverges with a small angle ($\theta_\parallel$) in the parallel direction [12]. For the diode laser used in this study $\theta_\perp = 38°$ and $\theta_\parallel = 10°$ [11].

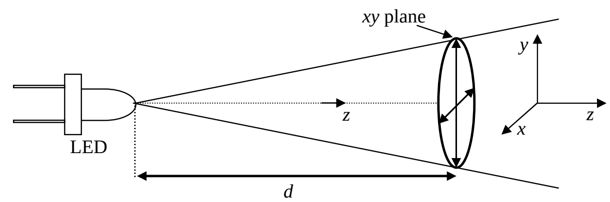

Figure 2: Schematics displaying x and y scanning method of a diverging radiation pattern from LED in a plane at a distance d and its irradiance is studied along z as a function of separation distance d.

4 Experimental Procedure

An irradiance pattern describes the relative light strength in a given direction from its source. In order to study irradiance pattern of an LED, it is driven with a sufficiently high power to obtain an intense light output. At a fixed distance, the projection of LED's radiation beam on a plane is nearly a circle or an ellipse of low eccentricity. If z is taken as the direction of the propagation of LED's radiation, then the radiation pattern of LED in three dimensions can be characterized first by scanning the beam in two mutually perpendicular directions x and y, in the xy plane (figure 2) at a fixed d. This is referred as the first characterization. The variation of LED's irradiance along z direction as a function of d is referred as second characterization.

In the first characterization, two detectors are placed one after the other at a distance of d = 3 cm from LED in a plane perpendicular to the propagation of beam. In this plane, radiation pattern is scanned using a

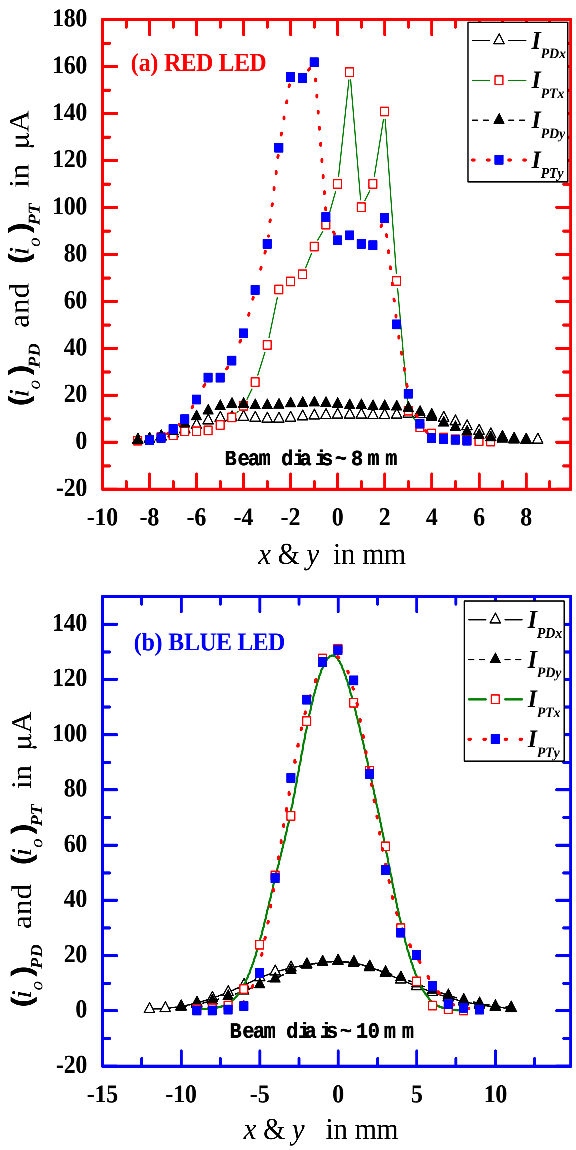

Figure 3: Radiation pattern of LEDs as measured with a photo diode (PD, △ and ▲) and with a photo transistor (PT, □ and ■) in two mutually perpendicular directions x and y, shown as a plot of current (in μA) as a function of x and y for (a) red LED and for (b) blue LED.

XYZ translation stage in steps of 1 mm along x and then along y, till detector senses the radiation. Care is taken to ensure that both the detectors pass through an approximate center of the pattern in both the scans.

Since LED emits radiation anisotropically, one must choose a reference point on irradiance for its study along beam propagation direction 'z'. Peak irradiance of its pattern is chosen for two reasons:

1. light can be detected even at longer distances and

2. alignment of peak irradiance (optical symmetry axis) from a diverging beam in a given direction is simpler than at any lower irradiance level.

Whenever radiation from LED has a single peak, LED is aligned in such a manner that its peak irradiance is along the center of optical rail. Otherwise, misalignment of radiation from an anisotropic radiator like LED leads to faulty results. Separation distance is increased in suitable steps from 5 cm to around 45 cm and corresponding output current data is collected. Analysis of this data is discussed under the results section.

However, use of this procedure for a study of radiation pattern with multiple peaks is cumbersome. Normally in such patterns, peaks are off the beam center which lead to problem of aligning the diverging LED's radiation beam. When a peak of such radiation is aligned, error in the measured data increases.

5 Results and Discussions

5.1 Irradiance profile of LED

5.1.1 In a plane perpendicular to beam propagation:

The irradiance patterns of red and blue LEDs with photo diode and photo transistor are measured in two directions x and y, at a distance of $d = 3$ cm and they are shown in figure 3. The radiation pattern of blue LED has a single peak which is symmetric with respect to peak (figure 3(b)), whereas red LED has two peaks in each measured directions x and y and their positions are not the same (figure 3(a)). For a given irradiance, the current data from a photo transistor has a gain factor 'G' with respect to a photo diode [8, 13]. Due to this, for a given irradiance, signal from a photo transistor is stronger than that from a photo diode in all the measurements.

The beam diameter (spot size) can be estimated from 3(b) as that width which contains almost 85% of the total light power [9]. The width of the beam along x is nearly the same as that along y, suggesting a circular pattern for blue LED with a diameter of nearly 10 mm at $d = 3$ cm. In the case of red LED this estimation is slightly difficult due to multiple peaks in its irradiance pattern, which are attributed to defect in the manufacturing process of LED. Its diameter is found to be ≈ 8 mm at $d = 3$ cm.

Normally, irradiance profile is represented in polar plots which do not depend on d [2, 3]. Plane angle θ is estimated from the peak intensity as $\theta_x = \tan^{-1}(x/d)$ or $\theta_y = \tan^{-1}(y/d)$. Angular distributions of LED's radiation pattern is represented by $\theta_{1/2}$ values which are the view angle when radiant intensity is half of the value at $\theta = 0°$. More consistent $\theta_{1/2}$ values of LED's radiation are obtained at separation distances greater than 10 cm [2]. The $\theta_{1/2}$ values are slightly inconsistent and hence slightly higher at lower separation distances [2]. Measured '$\theta_{1/2}$' value with this method for blue LED is 14° at $d = 3$ cm. Therefore it is expected that the consistent $\theta_{1/2}$ for the blue LED to be slightly lower than 14°. For an LED with $\theta_{1/2} > 10°$ the angular dependence of irradiance on power law measurements can be neglected [2]. Therefore, such measurements are not carried out here for the LEDs studied for which $\theta_{1/2} >$ 10°.

5.1.2 Along beam propagation:

Along beam propagation direction z, radiation is expected to describe some power law. Therefore, initially, three detectors viz., two photo diodes (PD1 and PD2) and a photo transistor (PT) are used for this purpose.

Direct Method:

A plot of i_o versus $1/d^2$ is drawn for all the three detectors for red LED and two detectors (PD1 and PT) for blue LED which are shown in figure 4(a) and figure 4(b) respectively.

A linear fit to data is carried out for all the data sets using Origin software (Version 8.1, OriginLab Corporation). Apparently the data describe straight lines as shown in figure 4(a), but the slopes 'k' of the data sets are not

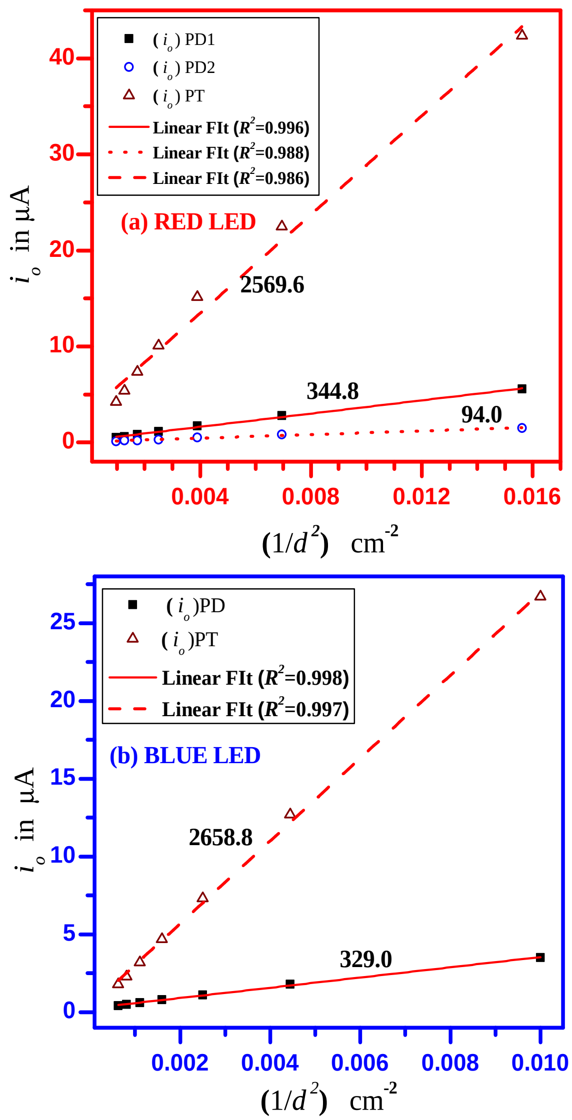

Figure 4: Plot of i_0 versus $1/d^2$ for (a) red LED measured with three detectors, viz., first photo diode (PD1-■), second photo diode (PD2- ○) and a photo transistor (PT-△) and for (b) blue LED with two detectors (PD1 and PT). Linear fit to data in both plots are done using Origin software.

unique for three detectors even with the same source. This indicates that the slope value is dependent on the type of detector used. Interestingly for a given detector, slope values 'k' with two different LEDs in figure 4(a) and 4(b) are nearly the same, which only shows that radiant intensities of red and blue LEDs are nearly the same.

Further, the method does not clarify which curve among the three, actually describes inverse square law of radiation. A close examination of plot reveals that, the linear fit to the data is imperfect. Therefore, the direct method does not reflect convincingly, correct behaviour of radiation in relation with distance. The second photodiode (PD2) has low output value as compared to the first one (PD1). Hence it is not used for further studies. A similar explanation holds good for the curves in figure 4(b). In some Indian institutions this direct method is used to verify the distance dependence of radiation and erroneously conclude that radiation describes inverse square law from an apparent straight line through the data.

Power Law Estimation:

For best illustration of the method, photo diode (PD1) data for blue LED's radiation is discussed here. The power exponent 'n' of distance with radiation is obtained from the plot of $\log i_0$ versus $\log d$ as ≈1.72 (figure 5(a)). This is lower than the expected value of 2.00. This shows that an apparent straight line fit to the data as in the direct method does not reflect inverse square law behaviour. One of the reasons for this discrepancy, is suspected to be in the measured d value. Since d is measured between the tip of LED and the tip of detector according to the published literature [2, 8]. Exact location of light emission in LED and exact location of light detection in the detector are different to the measured d. Therefore the measured separation distances need corrections.

To make an estimation of correct separation distance, a plot of $[1/(i_0)^{1/2}]$ versus d is drawn (figure 5(b)). If the measured 'd' values are correct, then a straight line fit to data must pass through (0,0) point in this plot, which in most cases do not happen. The fit line is extrapolated to obtain intercept along d. This gives a measure of distance 'd_c' needs to be corrected, which is '-2.10' cm for the case studied. A negative d_c indicates an under estimation of measured separation distance. This sign is acceptable here, as the separation distances are measured between the tip of LED and the tip of detector. Then correct separation distance r between LED and the detector is calculated as, $r = d - d_c$. If $d_c < 0$ then $r > d$ and vice versa. An over estimation of distance d would give a positive d_c value. With correct distance r, (2) changes to a new relation,

$$E = I/\left(d - d_c\right)^2 = I/r^2 \qquad (6)$$

With this correction, $r > d$, data points shift towards higher d values in a plot of $\log i_0$ versus $\log r$ as compared to the previous case (figure 5(a)). It is found that the effect of d_c on d is more at shorter distances as they are of same order than at longer distances. This correction changes the slope of the curve to 2.01±0.042.

By using two detectors (PD and PT), this analysis is repeated with all other sources mentioned in the section 3 and the results are

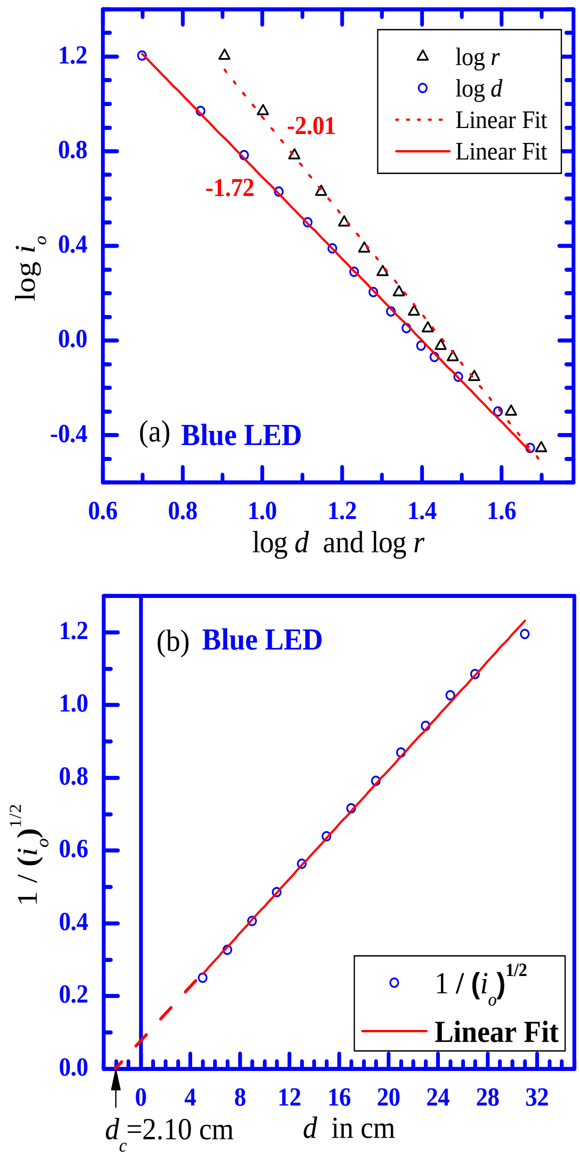

Figure 5: (a) Plot of $\log i_0$ versus $\log d$ (○) and $\log i_0$ versus $\log r$ (△) for blue LED as measured by a photo diode and (b) A plot of $1/(i_0)^{1/2}$ versus d to determine correction distance d_c.

Source	Detector	n_{before}	d_c (cm)	n_{after}	R^2
Blue LED	PD	-1.72	-2.10	-2.01 ± 0.042	0.994
Red LED	PD	-1.68	-2.53	-1.99 ± 0.016	0.999
Blue LED	PT	-1.94	-0.60	-2.01 ± 0.014	0.999
Red LED	PT	-1.88	-0.98	-1.99 ± 0.023	0.999
LD (open)	PT	-1.88	-1.35	-2.01 ± 0.041	0.995
LD (open)	PD	-1.63	-3.84	-2.06 ± 0.053	0.992
IL	PD	-1.85	-4.66	-2.06 ± 0.017	0.997
IL	PT	-2.18	+3.08	-2.02 ± 0.026	0.999

Table 1: Fit parameters of curves in figure 6(a) as explained in figure 5.

shown in figure 6(a). For a given light source, PT data are shifted vertically upwards from PD data at all irradiances due to the gain G in PT.

The fit parameters of all the curves of figure 6(a) are given in table 1. In case of laser diode, distance is measured from the tip of the detector to tip of the casing in which laser diode is embedded. Therefore d_c values obtained are higher than those obtained with LEDs for both the detectors. In case of incandescent lamp (IL) with PD detector distances are measured between the tips of source and detector. With incandescent lamp and PT system, $n_{before} > 2.00$, due to the reason that distance is measured from the center of the bulb near filament to the tip of PT. This is carried out here to demonstrate that even a positive 'd_c' can result while correcting for separation distances. Since incandescent source is brightest among the sources, the measured distances are extended up to 140 cm from 15 cm. Importantly, these measurements with uncalibrated detectors demonstrates that even for isotropic radiators like IL, correction of d is necessary before using such systems for any other measurements that depends on inverse square law behaviour.

In table 1, the third and fifth columns give the exponent of distance 'n' before and after correction of the separation distance (d_c-fourth column) respectively. The n_{after} values for red LED being less than -2.00 even after correction in 'd' indicates a source of error. This source is suspected to be due to the presence of multiple peaks in red LED pattern leading to alignment error at all separation distances. The data of the sixth column gives the co-efficient of fit (R^2) to the n_{after} data set. A close proximity of R^2 to 1 indicates better the fit to data.

Nonlinear Curve Fit:

Instead of a linear curve, a nonlinear curve can be drawn for the same data and curve can be analyzed with the help of a computing system. The data set is normalized with the exposed area A of each detector and a modi-

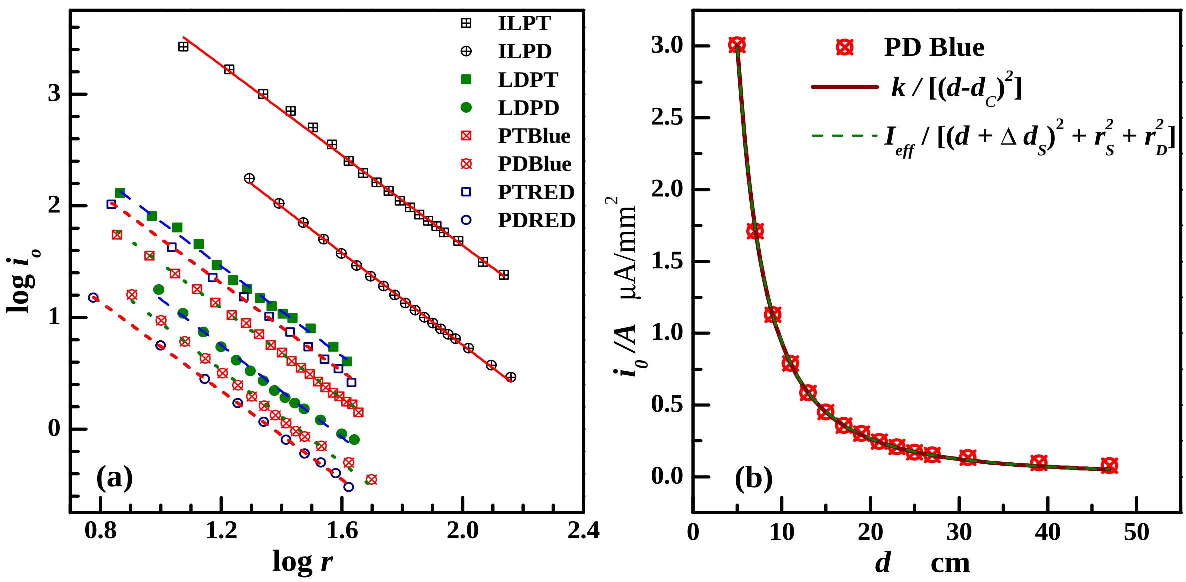

Figure 6: (a) Plot of $\log i_0$ versus $\log r$ with a photo diode (circles) and with a photo transistor (squares) for incandescent lamp (⊕ and ⊞), laser diode (● and ■), blue LED (⊗ and ⊠) and red LED (○ and □). (b) Plot of i_0/A versus d for a photo diode and blue LED system (⊗). Data points are fitted with (7) (——) and with (8) (- - - -).

fied of relation (6) is used to fit the curve with free parameters 'd_c' and 'k'($\propto I$, intensity of radiation).

$$i_o/A = k/\left(d - d_c\right)^2 \tag{7}$$

Figure 6(b) shows a nonlinear curve fit using (7) for the data obtained with PD and blue LED system. This procedure is extended for the remaining cases of measurement with LEDs and the results are given in table 2. Estimation of '$-d_c$' from power law method requires two plots whereas it can be obtained from a single plot with a nonlinear curve fit using (7). In addition, the latter method gives more reliable and reproducible values of '$-d_c$' due to the use of second free parameter k. Little more discussion on this topic is provided at the end of next section.

5.2 Applicability of the method

Detector output measurements are more accurate when they are closer to the source where it can receive a high percentage of radiation, whereas the measurements of 'd' are more accurate at large distances. In contrast, any actual source, barring collimated radiation sources like lasers, is of finite size. Due to finite size, irradiance from such sources describe the inverse square law of radiation provided the measurements with a detector are

LED	Detector	k (arb. units)	$-d_c$ (cm)
Blue	PD	$(1.197 \pm 0.017)\times10^2$	1.32 ± 0.05
Red	PD	$(1.068 \pm 0.009)\times10^2$	0.17 ± 0.03
Blue	PT	$(7.514 \pm 0.113)\times10^3$	0.53 ± 0.04
Red	PT	$(1.390 \pm 0.021)\times10^4$	3.24 ± 0.06

Table 2: Fit parameters 'd_c' and 'k' using (7) for all the curves in figure 6(a) as explained in figure 6(b).

carried out at a separation distance of about 10 times the size of the source [14]. This holds true whenever the dimensions of the source or of the detector are not small compared to d [5, 14].

It was shown that with calibrated detectors radiation from LEDs describe modified inverse square law [2, 5]. Therefore, in the process of determining the correction distance 'd_c' for a particular data set, it is assumed that radiation describes inverse square law. In power law method it is equivalent to forcing the distance data to describe inverse square law, but the method helps in estimating the error in d. However, reader is advised to be cautious because, in some systems this method can also yield spurious values of d. This can be identified with the knowledge of unaccounted length in d in such systems.

The sum of unaccounted distance in LED and in detector (PD or PT) from their tips is of the order of 1 cm. For such systems $d_c < 1$ cm. Measurements with PT satisfies this requirement here whereas those with PD do not for the same sources (see table 1). This encourages the use of a PT over a PD for any further characterization of LEDs radiations. Therefore, a high value of d_c (> 1 cm) with PD implies the presence of a source of error inherent to PD other than d. Certainly, the measurements of separation distance 'd' reported here are carried out with a better accuracy using an optical rail having graduations of 1 mm. An attempt is made here to explain the discrepancy.

A method that takes into account of the effective sizes of source and detector while determining the nature of radiation using a modified inverse square law was developed by Manninen *et al.* This method is based on two aperture approximation of LED source and detector and the theory predicts that irradiance of LED source follow the relation [2, 10]:

$$E\left(d\right) = \frac{I_{eff}}{\left(d + \Delta d_s\right)^2 + {r_s}^2 + {r_d}^2} g\left(d\right) \qquad (8)$$

Here, $g\left(d\right)$ is the multiplication factor which is close to unity; $d + \Delta d_s$ is the physical distance between the source and the detector; Δd_s is the offset distance of the source from its physical location due to encapsulation of LED; r_s and r_d are effective radii of

LED	Detector	I_{eff} (arb. units)	Δd_s (cm)	r_s (cm)	$(r_s)_{error}$
Blue	PD	$(1.193 \pm 0.053)\times10^2$	1.30 ± 0.39	-4.26×10^{-5}	3.93×10^4
Red	PD	$(1.004 \pm 0.019)\times10^2$	-0.41 ± 0.17	-2.13	0.29
Blue	PT	$(7.621 \pm 0.637)\times10^3$	0.63 ± 1.85	2.51×10^{-4}	1.22×10^5
Red	PT	$(1.389 \pm 0.071)\times10^4$	3.24 ± 0.55	-2.34×10^{-4}	1.14×10^5

Table 3: Fit parameters of the 'i_0/A' versus 'd' curves of all the LED's data in figure 6(a) (see figure 6(b) for blue LED and PD system) using (8) with $r_d = 0.035$ cm for PT and $r_d = 0.130$ cm for PD.

the virtual source and detector (aperture). For two LEDs and two detectors, plots of i_0/A versus d are drawn, and data are fitted using (8) with $r_d = 0.035$ cm for PT and $r_d = 0.130$ cm for PD with three free fitting parameters $I_{eff}, \Delta d_s$ and r_s. and results are shown in the table 3.

The condition required for an LED to serve as a point source is that, its encapsulation must behave as a moderate lens which is identified by the value of r_s parameter. If $r_s \approx 0$ then LED behaves as a point source [2].

Except red LED and PD system, all other systems produced $r_s \approx 0$, but with several orders of higher magnitude of uncertainty (sixth column of table 3). The uncertainty values of r_s for LEDs studied by Manninen *et al* were not reported [2]. The goodness of the fit to data with (7) in figure 6(b) requires that same data when fitted with (8), r_s value should approach zero in the latter method. It is believed here that, this requirement increases uncertainties in r_s values to very high level of the order of 10^5.

The results of table 3 indicate that blue LED behaves as a point source. In case of red LED and PD system $|r_s| > 0$ and $|r_s| > |\Delta d_s|$. They suggests that red LED does not serve as a point source [2]. However data with same red LED using PT provides $r_s \simeq 0$. This duality of results with red LED indicate a source of error that lies within PD [2]. This result of PD correlates with the earlier result obtained using power law method. Note that (8) is derived for a well calibrated detector. In case of an uncalibrated detector an improvement in the relation (8) is required with an additional term associated with the detector [15]. This term is defined as an offset of the detector's virtual plane position through certain Δd_D from the detectors aperture plane [15]. The effect of Δd_D on the measurements seems to be significant only on red LED and PD system. This Δd_D is not attempted to estimate here.

For a detector with a small pin hole aperture $r_d \ll d \approx 0$ and with $r_s \approx 0$, (8) reduces to (7) with $\Delta d_s = -d_c$. Figure 6(b) illustrates the fitted curves to data by (7) and by (8) for PD and blue LED system. These fitted curves found to overlap each other in the figure 6(b). This suggests that the assumptions, viz., $r_d \approx 0$ and $r_s \approx 0$ are valid.

The use of two fitting parameters in (7) and three in (8) with $r_s \approx 0$, seems to produce values of k to be in fair agreement with I_{eff}. Also, '$-d_c$' is in fair agreement with Δd_s, in all the systems studied. Importantly, the magnitude of uncertainties in all the fit parameters are smaller using (7) than that using (8). Therefore for LEDs with low value of r_s, and one can use the simplified relation (7) instead of (8) for obtaining better results.

Optical power radiated or external efficiency of an LED are inherent properties of that LED. In an undergraduate laboratory, they are determined by placing a detector at certain separation distance from the source. Therefore, these properties of LEDs depend mainly on the power law behaviour of LED's radiation. Whenever ordinary detectors are used for measurements then following precautions must be taken care of:

1. Alignment of peak irradiance along the direction of measurement.

2. Ensure that LED being probed has an angular distribution ($\theta_{1/2}$) value greater than 10°.

3. Use either power law or nonlinear curve fitting methods to know the true working of systems along beam propagation direction.

4. When power law method is used, then make sure that a prior knowledge of unaccounted distance between source and detector is in hand.

When external efficiency of an LED measurements are carried out, an unambiguous efficiency of blue LED is obtained with a photo transistor at all separation distances above 7 cm, suggesting that inverse square law of radiation is described by that system only at seperation distances d above 7 cm [16].

The exponent of distance n_{after} in all the measurements (fifth column in table 1) is nearly -2.00 with margin of error shown. This suggests that even anisotropic radiators like LED and diverging laser exhibit inverse square law behaviour. The power law method holds good even for an isotropic radiator like incandescent lamp. Therefore it is extended for β and γ nuclear radiations using a GM detector (results are not shown) and method's validity for nuclear radiations are also tested.

6 Conclusions

The radiation emitted by anisotropic radiators like LEDs were studied using inexpensive photo diode and photo transistors in three dimensions. In the direct method, it was shown that slope k value depends mainly on the detector type used, however the method do not provide the true nature of relation between radiation with distance. In the power law method, it was found that with a prior knowledge of expected correction distance d_c for a measuring system, one can identify a detector that reproduces inverse square law of radiation to the best extent. In the present study photo transistor does satisfies this requirement. Further, it was shown that knowledge of peak irradiance position from an anisotropic source is necessary to obtain better results. Limitations and validity of the power law verification method were discussed. Any uncalibrated detector can be tested on its working ability with this procedure. If nonlinear curve fitting for the data is feasible, then two aperture approximation method or its simple version in the form of relation (7) can be sued. Essentially, (7) was found to five better results with lower errors in the fit parameters for LED's with $r_s \approx 0$ and with $\theta_{1/2} > 10°$.

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