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Determining the efficiency of optical sources using a smartphone's ambient light sensor

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Abstract

This work reports the use of a smartphone's ambient light sensor as a valuable tool to study and characterize the efficiency of an optical source. Here, we have measured both luminous efficacy and efficiency of several optical sources (incandescent bulb and halogen lamp) as a function of the electric power consumed and the distance to the optical detector. The illuminance of LEDs as a function of the distance to the optical detector is characterized for different wavelength emissions. Analysis of the results confirms an inverse-square law of the illuminance with the detector–source distance and shows good agreement with values obtained by classical experiments. This experience will trigger awareness in students in terms of sustainability, light propagation and efficiency of different optical sources.

Keywords: luminous efficiency, smartphone, ambient light sensor

(Some figures may appear in colour only in the online journal)

1. Introduction

The M-learning concept extends widely among the teaching community and recently, together with the use of familiar equipment to students, has been explored to perform new physics laboratory practices more attractive to them. Electronic devices such as digital cameras [1], webcams [2], optical computer mice [3, 4] and game controllers [5–7] allow us to determine fundamental physics properties through the design of new and interesting experiments.

Among all these electronic devices, the widespread use of smartphones by most students and the large amount of sensors contained in them offer an invaluable opportunity to perform new teaching strategies. Moreover, the constant evolution of free apps to extract information acquired by the smartphone's sensors supports this initiative. This attractive tool for scientific demonstrations and experimental measurements can 'enrich educational opportunities for learners in diverse settings' [8]. Several examples of the design of new physics laboratory practices have been recently presented showing the use of smartphones' sensors in physics education in different topics such as mechanics [9–13], optics [14–16] and acoustics [17, 18].

Regarding the exploitation of the different optical sensors of smartphones, Hossain and coworkers [19] proposed the use of the camera of a smartphone as a fluorimeter with good agreement between their results and the values obtained by a conventional fluorimeter. Vieira *et al* [20] carried out a first approach to the use of a smartphone's ambient light sensor to describe the variation of light intensity with the inverse-square law of distance. Using this physics law, our group [15] has characterized the variation of light intensity to describe simple harmonic and damped oscillatory motion with the ambient light sensor. This paper paved the path for considering a smartphone's ambient light sensor as an accessible optical detector. In addition, the study of electric power consumed by several optical sources could raise students' awareness about the importance of using more efficient devices.

In the present work, we go further presenting a new laboratory experiment based on the measurement of the luminous efficiency and efficacy of several optical sources by using the smartphone's ambient light sensor in order to compare their properties. We expect that the use of their own smartphones will trigger students' interest and motivation to perform the laboratory practice and consequently reinforce their curiosity to carry out their own home-made experiments.

2. Methods

The luminous efficacy of a light source defines how well a device transforms electrical energy into luminous energy. It is determined by an equation which expresses the ratio between the luminous flux (ϕ) and electrical power (P):

$$\eta = \frac{\phi}{P}. \tag{1}$$

In the literature it is possible to find a similar parameter defined by light emitted as a function of the maximum theoretical light emission (683 lm W^{-1} defined at 555 nm) [21]. The choice of this wavelength is not random but is that at which the human eye is more sensitive. This value is obtained from blackbody radiation and is called luminous efficiency, expressed as a percentage.

In the particular case of smartphones, they are usually equipped with a light sensor that allows the brightness of the display to be adjusted based on environmental lighting to optimize battery life. This light sensor uses a photodiode, in combination with a filter, to adjust its spectral sensitivity to the sensitivity of the human eye. This device is able to measure the illuminance (E), which is calculated by the luminous flux (ϕ) per unit area (A) as expressed by

$$E = \frac{\phi}{A}. \tag{2}$$

The size of the different optical sources used in this work, smaller than the detector–source distance, allows us to consider them as point sources. In this case, the energy in a certain region is determined by the amount of luminous flux that crosses a defined area. In the

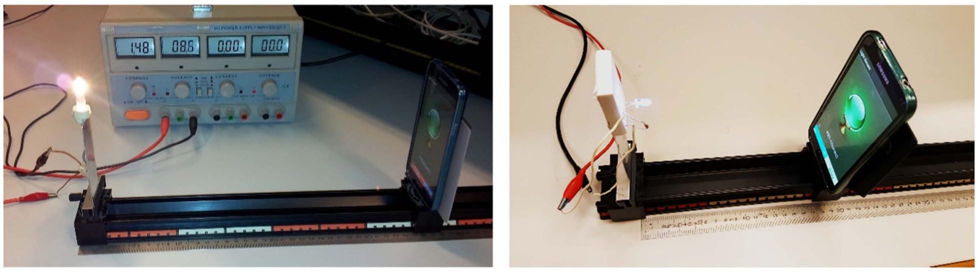

Figure 1. Experimental set-ups to measure the luminous efficiency of an optical source using a smartphone's light sensor.

case of a point source, the luminous flux is propagated in all directions and is distributed over a spherical surface. The illuminance measured with a point detector is approximately equal to the density of luminous flux projected by the optical source. Thus, the illuminance can be expressed as

$$E = \frac{\phi}{4\pi r^2}. \tag{3}$$

The experimental measurement of these magnitudes requires a point detector or a small surface to determine the luminous flux and consequently the illuminance. Here, we propose the simple experimental set-up shown in figure 1 in order to determine the illuminance of different optical sources and considering the smartphone's ambient light sensor as a point detector. The optical source has been placed on the optical bench in a darkened room and connected to a variable power supply in order to control the electrical power provided to it. A smartphone (Samsung Galaxy S5) has also been placed on the optical bench with the center of its light sensor facing the light bulb. We have used the 'Sensor Box for Android v5.0' free app [22] to quantitatively determine the luminous intensity that reaches the smartphone's light sensor. The illuminance provided by the optical source was measured as a function of its distance to the light sensor, and as a function of the electrical power supplied.

The data measured by the smartphone's ambient light sensor have been correlated with those given by a calibrated conventional luxometer. These results show a perfect agreement between both measurements. Analysis of the variation of the measurement with angle has shown that error in the position of the smartphone should not affect the value obtained. On the other hand, we checked the validation of the measurement with the ambient light sensor for different wavelengths and we observed a perfect agreement using a yellow filter in the lamp but an overestimation (underestimation) when using a red (green) filter. These correlation factors are important enough to be taken into account. The illuminance values presented in this work have been corrected using these factors (1.3 for red and 0.64 for green).

In this work, we have used an incandescent bulb, a halogen lamp and four light emission diodes (LEDs) to compare their illuminance ranges and the change of their efficiency with respect to the electric power supplied.

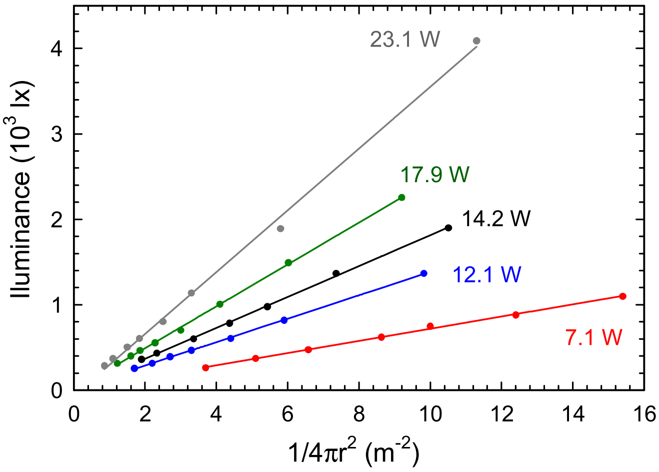

Figure 2. Experimentally measured illuminance of an incandescent bulb versus the inverse of a spherical surface of radius r (symbols) for each electric power supplied. Least-square fits (lines) serve to obtain the values reported in table 1.

3. Results and discussions

3.1. Incandescent and halogen lamps

An incandescent bulb is formed by a wire filament through which an electric current passes, making the filament heat up enough to radiate in the visible range. The bulb isolates the filament avoiding its oxidation by the presence of an inert environment or vacuum. Here, we have studied the illuminance of an incandescent bulb (Osram 7506) as it is the most common optical source used in a basic laboratory. The illuminance was measured as a function of the distance between the light source and the smartphone's light sensor, as well as a function of the electric power consumed. The distance range used between the light source and the smartphone's light sensor varied from (8.4 ± 0.1) cm to (30.5 ± 0.1) cm and the consumed electric power ranged between (7.10 ± 0.19) W and (23.1 ± 0.3) W. The experimental illuminance data collected by the smartphone's light sensor have been used to estimate the luminous flux according to equation (3), considering that the luminous energy is equally distributed along spherical surfaces. The representation of the experimental illuminances at several electric powers as a function of the source–detector distance is shown in figure 2. These experimental data display a clear quadratic dependence with distance and can be fitted using least squares. All these fits show very good correlation coefficients close to 0.99. The large error observed in the y-intercept value given by the fit can be explained in terms of: (i) the incandescent bulb cannot be considered as a point source at short source–detector distances; and (ii) the environmental light conditions, which should give a constant illuminance value. The luminous efficiency of the incandescent lamp increases with the increase of the electric current, which ranges between 1.5% and 2.3%.

The difference between the halogen lamp and the incandescent bulb lies in the presence of a halogen environment inside the bulb. This produces a halogen cycle chemical reaction with the material of the filament (typically tungsten) which is evaporated and redeposited back onto the filament. Thus the lifetime of the source is extended, allowing it to operate in a high electric power range and increasing its efficacy. In this experiment, we have characterized a halogen lamp (Osram 64427S–58663) using similar distance ranges between the

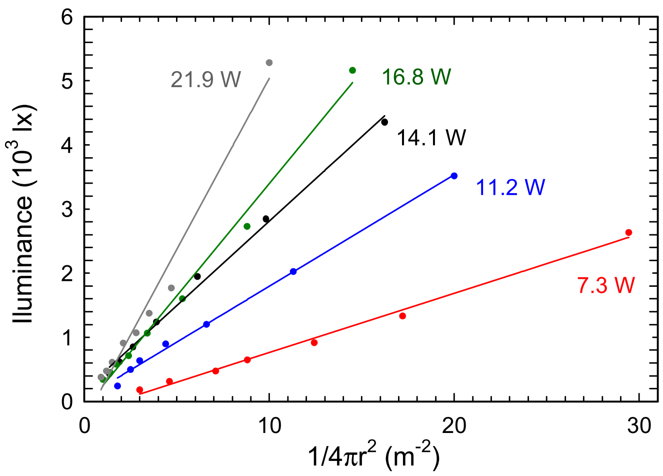

Figure 3. Experimentally measured illuminance of a halogen lamp versus the inverse of a spherical surface of radius *r* (symbols) for each electric power supplied. Least-square fits (lines) serve to obtain the values reported in table 1.

Table 1. Luminous flux, luminous efficacy and luminous efficiency of incandescent and halogen lamps obtained for different electric powers.

	Consumed electric power	Emitted luminous flux (lm)	Luminous efficacy (lm W^{-1})	Luminous efficiency (%)
Incandescent	(7.10 ± 0.18) W	71.3 ± 1.4	10.0 ± 0.5	1.5
	(11.9 ± 0.2) W	136.9 ± 1.2	11.5 ± 0.2	1.7
	(14.2 ± 0.3) W	181 ± 2	12.7 ± 0.3	1.9
	(17.9 ± 0.3) W	245 ± 2	13.7 ± 0.3	2.0
	(23.1 ± 0.3) W	361 ± 8	15.6 ± 0.5	2.3
Halogen	(7.3 ± 0.2) W	92 ± 3	12.6 ± 0.8	1.9
	(11.2 ± 0.2) W	174 ± 5	15.8 ± 0.7	2.3
	(14.1 ± 0.3) W	263 ± 8	18.6 ± 1.0	2.7
	(16.8 ± 0.3) W	350 ± 12	20.8 ± 1.1	3.1
	(21.9 ± 0.3) W	530 ± 30	24.3 ± 1.8	3.6

light source and the smartphone's light sensor, (8.9 ± 0.1) cm to (30.0 ± 0.1) cm, and a similar consumed electric power range, (7.3 ± 0.2) W and (21.9 ± 0.3) W. The experimental illuminance is shown in figure 3 as a function of the source–detector distance for several electrical powers provided. As in the case of the incandescent bulb, the halogen lamp is considered a point optical source to first approximation. The correlation factors of the least-square fits exhibit values close to 0.99, which indicate the validity of the inverse-square law.

Equations (1) and (2) allow us to determine the luminous efficacy and efficiency for each electric power provided (table 1). The typical value of the luminous efficacy for a halogen lamp (20 lm W^{-1}) [23–25] is close to that obtained for the highest electrical power provided, which indicates the validity of the method used. The halogen lamp increases the luminous efficiency, which ranges between 1.1% and 3.4%, in good concordance with the efficiency reported for tungsten halogen lamps at the highest electric power in [26] (3%). The efficiency

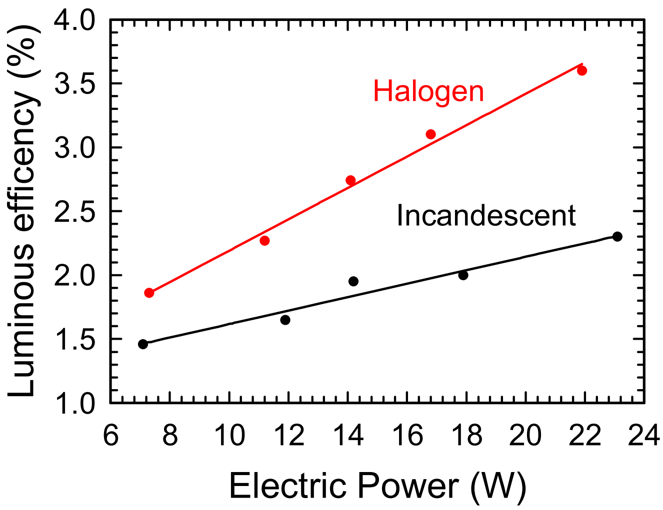

Figure 4. Measured luminous efficiency of incandescent and halogen lamps.

obtained in the halogen lamp is higher than that of the incandescent bulb for similar electric power supplied, which shows that the presence of the halogen gas allows higher temperatures to reach the filament.

Figure 4 shows a steady increase of the luminous efficiency as a function of the electric power for the incandescent and halogen lamps. The emission in incandescent bulbs behaves like an imperfect blackbody and requires a certain temperature to emit in the visible range according to Wien's displacement law. Both of them depend on the temperature reached in the tungsten filament. The increase of the electric power supplied leads to an increase of the temperature in the filament and, consequently, to a shift of the wavelength of the maximum optical emission towards values closer to that of the maximum theoretical light emission (555 nm), causing an improvement of the efficiency [27]. The presence of a halogen environment improves the efficiency of the halogen lamp with respect to the incandescent bulb due to the reconstructive effect of the halogen gas, which causes a higher filament temperature (higher illuminance) than the one obtained with the incandescent bulb. In this work, we have not exceeded the maximum electric power recommended by the manufacturer. Above the electric power recommended, the maximum optical emission could be at a higher wavelength than that at which the human eye is more sensitive (555 nm) or even the filament could evaporate too much, degrading it. All these factors will trigger a decrease of the luminous efficiency.

Besides the steady increase of the luminous efficiency with electric power, we have also observed a linear tendency between both parameters. Above 600 K, the temperature dependence of the tungsten filament with the electric power [28–30] follows a quasi-linear trend. This effect is due to the direct relationship between the electrical resistance of the cathode and the temperature raised to the power of 1.2 [28, 29]. According to Wien's displacement law, an almost linear behavior of the temperature with the electric power supplied leads to an almost linear behavior of the maximum emission wavelength with the same electric power. If the maximum emission wavelength of the tungsten lamp gets closer to the wavelength where the human eye is more sensitive (555 nm), then the optical efficiency should increase in the same way. This explanation allowed us to approximate the fit of our experimental results to a linear equation.

Table 2. Voltage supplied to the circuit, and voltage, current and electric power used by each LED, together with luminous flux calculated for each LED.

	Voltage supplied (V)	Voltage in LED (V)	Current (mA)	Electric power (mW)	Emitted luminous flux (lm)
Green	24.0 ± 0.2	2.4 ± 0.1	18.1 ± 0.4	43 ± 3	0.15 ± 0.02
Yellow	24.0 ± 0.2	2.1 ± 0.1	18.3 ± 1.0	44 ± 2	0.24 ± 0.03
Red	24.0 ± 0.2	2.0 ± 0.1	18.4 ± 0.8	44 ± 2	0.54 ± 0.06
Ultra-bright	24.0 ± 0.2	3.4 ± 0.1	19.2 ± 1.2	65 ± 2	11.9 ± 0.7

3.2. LEDs

A LED consists of a junction of two doped semiconducting materials (one p-type and the other n-type) forming a diode. Applying an electric current, the electrons flow from the n-type semiconductor towards the p-type semiconductor but not in the reverse. The electrons are recombined when they meet holes, releasing energy in the form of photons. The optimization of this process has permitted the manufacture of ultra-bright LEDs. These optical sources offer a higher illuminance for the same electric power. LEDs cannot be considered as a point source since they show directionality in their emission. This characteristic comes defined by the aperture angle (20° in this case) and the luminous flux is distributed over a spherical cap instead of a sphere. In this work, we have explored the efficacy of LEDs (825MR2C, 825MY8C, 825PG2C) emitting at different wavelengths and we have compared the results with an ultra-bright 10 mm white LED (140 000 mcd with $\sim$ 15° of apex aperture). The efficacy of LEDs emitting in the red, yellow and green has been obtained from the variation of the illuminance as a function of the LED–smartphone distance, and these values have been compared with those obtained for an ultra-bright LED. The characteristics of these devices are shown in table 2.

LED–smartphone distances are in the same range for all the LEDs studied. In particular, the distance between the light source and the smartphone's light sensor is in a range from (3.6 ± 0.1) cm to (17.4 ± 0.1) cm, similar to that of the incandescent or halogen lamp. On the other hand, the electric current consumed by the LEDs is much lower than the values supplied (see table 2). In order to avoid effects of efficiency drop [31], we have fixed the electric voltage and current to the optimal value provided by the manufacturer.

The comparison of these results with those given for incandescent and halogen lamps is inadequate since the origin of the light emission is completely different, as well as their kind of emission. The comparison of the results for the LEDs with those of the blackbody radiation maximum in order to calculate their efficiency can be considered unfounded. LED emission is not given by the temperature of the component materials (as happens with the incandescent and halogen lamps) but the recombination processes carried out between n-type and p-type semiconductors. On the other hand, the LED emission is by definition monochromatic. In the case of white LEDs, several spectral lines are overlapped in order to cover most of the visible spectral range in contrast with the continuous emission obtained in both halogen and incandescent lamps. Thus, values of efficiency as we have defined it would be unreal. However, LEDs show similar dependence on distance as incandescent and halogen lamps when the directionality of their emission is taken into account. Consequently, the light propagates through a spherical cap surface. The low electric power consumed by LEDs gives an average luminous efficacy higher than the incandescent and halogen lamps. Comparing LEDs

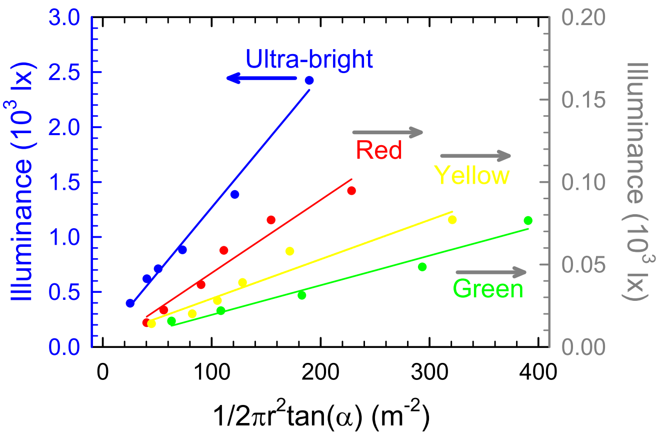

Figure 5. Illuminance as a function of the detector–source distance for LEDs emitting in different wavelengths and compared with an ultra-bright LED device. Iluminance for red, yellow and green LEDs are associated with the right *y*-axis whereas the value for the ultra-bright LED is associated with the left *y*-axis.

emitting at several wavelengths (figure 5), one can clearly see that the ambient light detector is optimized for low photon energies. On the other hand, the illuminance measured for the ultra-bright LED is one order of magnitude higher than the values obtained for usual LEDs, which reveals an increase of efficiency achieved with the same electric current.

4. Conclusions

We have successfully used a smartphone's light sensor and the Android application 'Sensor Box for Android' to measure the illuminance of three different optical sources. We have proved the inverse-square law dependence of illuminance with detector–source distance for all the quasi-point optical sources. These measurements allowed us to determine the luminous efficacy and efficiency of both incandescent and halogen lamps as a function of the electric power supplied using a least-square fit. We observed a steady increase of the luminous efficiencies obtained with the supplied electric power for both sources, which has been explained in terms of blackbody emission, Wien's displacement law and the relationship between resistance and temperature given in a tungsten filament. We have also proved the validity of the inverse-square law dependence of the illuminance with the detector–source distance for LEDs emitting at several wavelengths. The comparison of usual LEDs with an ultra-bright LED showed an increase of one order of magnitude of the illuminance obtained by the latter. These results should stimulate students to use their smartphones to perform their own experiments at home, which will raise their awareness of the importance of luminous efficiency.

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