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On the determination of the emission wavelength of an infrared LED with common laboratory instruments

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Abstract

This work demonstrates an experiment on the optoelectronic properties of a p–n junction suitable for students of undergraduate physics. It investigates, from an educational point of view, the origin of the wavelength of radiation emitted by a light emitting diode (LED) and determines the emission wavelength of an infrared LED without using precision instruments. The wavelength ranges were estimated for four LEDs emitting visible radiation using a common laboratory spectrometer and grating arrangement. The turn-on voltages of these LEDs and that of an infrared LED were estimated from their forward current–voltage characteristics. The wavelength of the infrared LED was determined by extrapolating the turn-on voltage versus the corresponding emission frequency plot for the visible LEDs. The variation was found to be nonlinear. The results were compared with standard results obtained from precision measurements, and reasonable accuracy was obtained.

1. Introduction

A light emitting diode (LED) emits radiation of a continuous spectrum over a range of wavelength with peak emission at a certain wavelength. The emission range may be within the visible, infrared or ultraviolet region depending on the energy band structure of the semiconducting material that the device is made of. By virtue of such wavelength-selective emission, LEDs have diversified fields of application including gas detection [1], aerosol detection [2], lighting for greenhouse plant cultivation [3], miniature multispectral sensor [4] and many others, as reviewed in the literature [5]. The above are subjects of rigorous research and the determination of the wavelength of emission is a vital component of the work. Obviously the measurement involves sophisticated and expensive spectrometric techniques.

Determination of the range of wavelength emitted by a glowing LED may be an interesting job for students in undergraduate laboratory. The spectrum of a common visible light source can be measured there with reasonable accuracy using a manual spectrometer and grating with good resolving power. The same method is expected to estimate, more or less correctly, the waveband of radiation emitted by a visible LED. The problem with similar estimation for an infrared LED is that human eye cannot observe the emitted radiation. The response of the eye to the radiation wavelength variation, popularly known as *photopic sensitivity*, is maximum at about 555 nm. The response of the eye to the radiation intensity variation, named *scotopic sensitivity*, is maximum at about 505 nm. Both the sensitivities rapidly fall beyond these wavelength regions and become almost zero in the infrared and ultraviolet regions. However, the infrared LED is a significant device from a practical point of view because of its implementation for remote control in home appliances, movement sensor and invisible illumination for night vision.

This work proposes an easy method to estimate the emission wavelength of an infrared LED with common laboratory equipment. It is expected to be an interesting experiment on the optoelectronic properties of a p–n junction for undergraduate students in physics. The turn-on voltages of four LEDs emitting visible radiation and that of an infrared LED were estimated from their forward current–voltage characteristics. The emission wavelengths of the visible LEDs were estimated with a manual spectrometer and grating arrangement. The wavelength of the infrared LED was determined by extrapolating the turn-on voltage versus the corresponding emission frequency plot for the visible LEDs. The correctness of the result was verified with the standard result obtained from precision measurements taken by other instruments.

2. Theoretical background

Absorption and emission in semiconductor are reversible processes [6]. Electrons in valence band can absorb photons with sufficient energy and rise to the conduction band. Conversely, downward transition to a lower energy state is possible with the emission of electromagnetic radiation. The latter is the case of the LED. It is basically a forward biased p–n junction diode. On applying the forward bias voltage the conduction band electrons on the n-side get uplifted to the conduction band of the p-side circumventing the potential barrier at the junction and subsequently recombine with holes in the p-side valence band emitting radiation of a characteristic wavelength depending on the energy band structure of the semiconducting material.

The standard equation for the current (I) through the p–n junction diode under forward bias voltage (V), as mentioned in the literature [7–10], is

$$I = I_0[\exp(qV/\eta kT) - 1], \tag{1}$$

where I_0 is the reverse saturation current caused by the thermally generated minority carriers. It is very feeble, of the order of microampere to nanoampere or even less at room temperature. It is a function of temperature and independent of the bias voltage. The symbol η represents a constant having a value between 1 and 2 depending on the semiconducting material. It characterizes the diode current for a particular type of semiconductor. The other symbols have their usual meaning, namely k is Boltzmann's constant, q is the magnitude of electronic charge and T is the absolute temperature.

The above concepts have been utilized on a number of occasions [11–15] to estimate Planck's constant (h) from the variation of the emission wavelength of the LEDs with corresponding forward turn-on voltage of different colours [11–14] and also from the voltage

decay across the LED after switching off [15]. There was a basic difference among the above approaches. Some researchers [11, 12, 15] assumed a certain 'turn-on' or 'diffusion' voltage V_o determined by extrapolating the tangent to the forward current–voltage characteristic curve of the p–n junction diode up to the voltage axis. Assuming V_o nearly equal to the band gap energy and considering direct recombination of charges within the semiconductor, the following formula was proposed:

$$qV_o = hc/\lambda = h\nu, \tag{2}$$

where h is Planck's constant, λ is the wavelength of the emitted radiation, ν is the corresponding frequency and c is the velocity of light in vacuum. Planck's constant was calculated from equation (2).

Other researchers [13, 14] challenged the above concept of determining V_o because it apparently indicates a finite value of voltage at zero current that the standard current–voltage relationship of a p–n junction diode (equation (1)) does not support. In addition, Morehouse [14] pointed out the possibility of the voltage drop across the ohmic resistance within the LED package and suggested the determination of Planck's constant by plotting the function $\eta\ln(I_0)$ against λ^{-1}. The graph represents a linear relationship, the slope being hc/kT. The parameters are defined with equations (1) and (2).

From the above discussion, this work has the following objectives. First of all, the apparent discrepancy among the above opinions must be explained. Moreover, Planck's constant is a well-known quantity that one can readily use. Instead of determining it again, one can calculate an unknown wavelength from the above formulations using the standard value of h. This is the basic idea of this work. At the same time, it is intended to investigate whether the above linear relationship (equation (2)) between V_o and ν is taken for granted. If not, the possible extent of error in the determination of the unknown wavelength is to be estimated.

Both the groups of researchers [11, 12, 15] and [13, 14] are correct from their own points of view. The gap can be bridged with the proper explanation of the forward current–voltage (I–V) characteristic curve of the diode as demonstrated in figures 1(a)–(c). Figure 1(a) shows the theoretical I–V curve generated with equation (1). The tangent at the elbow-like region of the curve cuts the voltage axis at some value $V1$. It is similar to the turn-on voltage used by the earlier workers. It appears to be a finite voltage value at zero current, but that is not actually so. The current is not zero but very small compared with the value at the top of the current axis. If we enlarge the lower portion of the current scale and also the corresponding voltage scale, the curve looks like that of figure 1(b). Again a voltage intercept is obtained at some lower value $V2$. If we further magnify the scale, the curve looks like that of figure 1(c). This time another voltage intercept $V3$ is found at a further lower value. Indeed this is the basic nature of an exponential curve like the present one.

Now the question is: which one should we call the 'turn-on voltage': $V1$, $V2$ or $V3$? The answer is obtained from page 59 of [9] quoted as: 'There exists a *cutin*, *offset*, *break-point* or *threshold* voltage below which the current is very small, less than 1% of the maximum rated value'. The different nomenclatures mean the same entity, namely the turn-on voltage discussed above. The same term is used in this paper because it is meaningful as regards the glowing of the LED. For most practical applications, diodes and LEDs operate with currents of the order of milliamperes. Therefore only $V1$ (and not $V2$ or $V3$) may be designated as the turn-on voltage because here the current enters the milliampere zone. The currents corresponding to the other two are of much lower value. In the case of LEDs, the turn-on voltage has been defined as the voltage at which the LED starts glowing [11, 12] or as the minimum voltage required for the current to flow through the LED [15]. Both are essentially

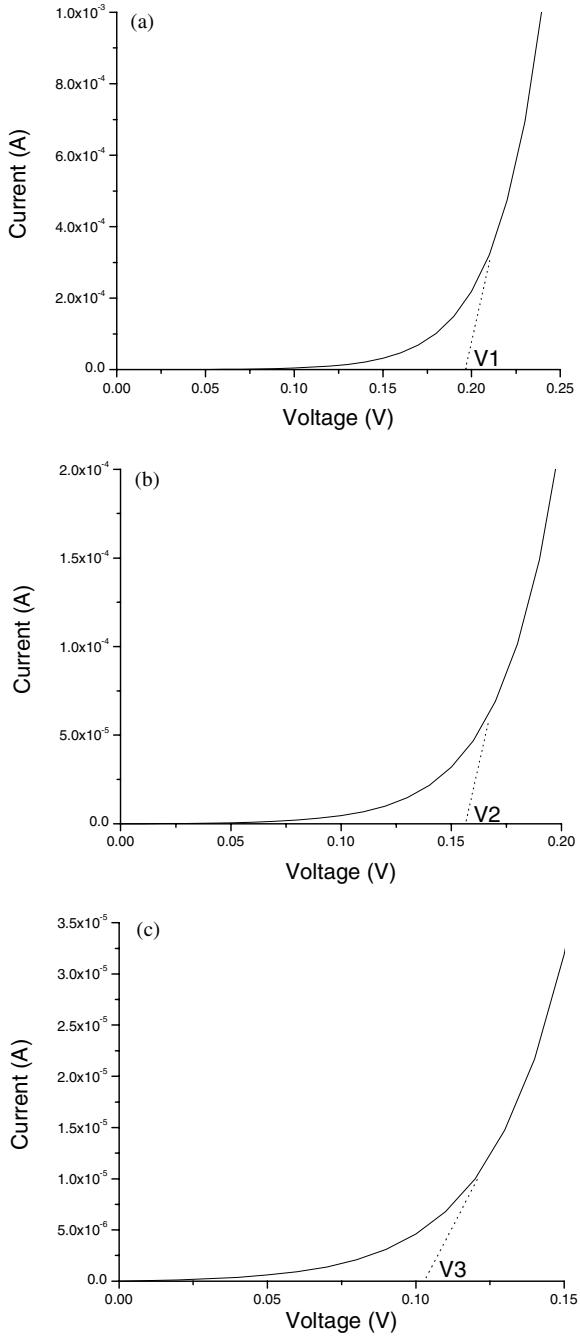

Figure 1. (a) Forward current–voltage characteristic of a p–n junction diode theoretically generated with equation (1), (b) the enlarged view of the smaller values of current and voltage and (c) further enlarged view. Parameters assumed: $I_0 = 1 \times 10^{-7}$ A, $\eta = 1$, $k = 1.38 \times 10^{-23}$ J K^{-1}, $q = 1.6 \times 10^{-19}$ C and $T = 300$ K.

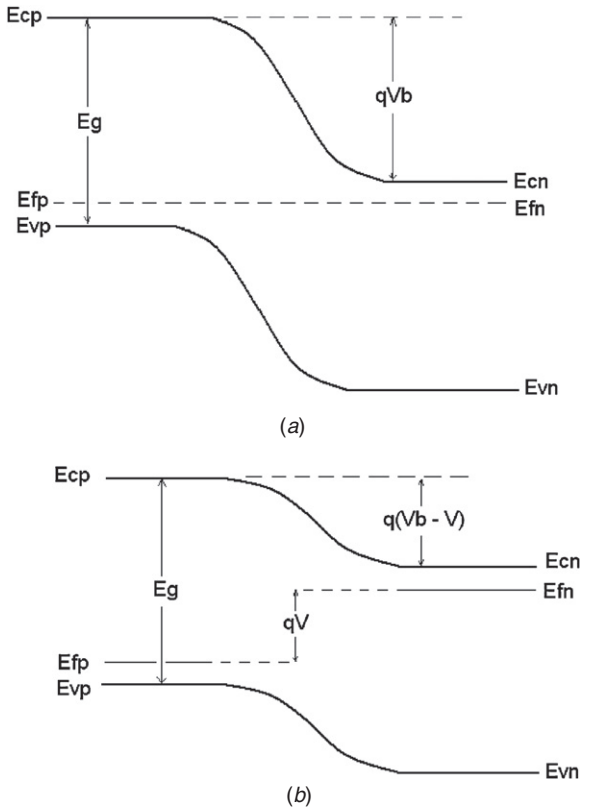

Figure 2. Simplified energy band diagram of a p–n junction (a) at equilibrium and (b) under forward bias voltage V. Symbols: E_g is the band gap energy of the semiconductor and qV_b is the potential barrier at the junction. E_c, E_v and E_f represent the conduction band edge, valence band edge and Fermi level, respectively, whereas the subscripts p and n represent the p-side and the n-side, respectively.

the same definition, as justified with the energy band picture of the p–n junction illustrated below.

Figure 2(a) shows the simplified energy band diagram of a p–n junction at equilibrium [10]. A potential barrier qV_b exists at the junction such that

$$qV_b = E_g - q(V_n + V_p), \tag{3}$$

where E_g is the semiconductor band gap, V_n represents the distance of the Fermi level from the conduction band edge on the n-side and V_p is the distance of the Fermi level from the valence band edge on the p-side expressed as

$$V_n = (kT/q)\ln(N_c/N_d) \tag{4a}$$

and

$$V_p = (kT/q)\ln(N_v/N_a), \tag{4b}$$

respectively. N_c and N_v are the effective densities of states in the conduction and valence band, respectively, N_d and N_a are the doping concentrations on the n-side and the p-side, respectively, and the other symbols have their usual meaning.

Fermi levels on the p-side and the n-side are aligned at equilibrium, as shown in figure 2(a). No current flows through the junction due to the presence of the potential barrier. Thus $I = 0$ at $V = 0$, which agrees with equation (1). However, when a forward bias voltage V is applied across the junction, Fermi levels on the two sides get shifted and the potential barrier is lowered to $q(V_b - V)$, as shown in figure 2(b). Equation (3) now changes to

$$q(V_b - V) = E_g - q(V_n + V_p) - qV. \tag{5}$$

Because of barrier lowering, current starts to flow across the junction. On increasing the bias voltage, the barrier reduces further and the current increases in agreement with equation (1). Ultimately, when the applied bias voltage acquires the same magnitude as that of the potential barrier, there remains essentially no barrier at the junction and the current flows in large amount. In the case of an ordinary diode, this condition is experimentally realized as the cutin voltage stated earlier [9] and in the case of a LED, it is observed as the turn-on voltage (V_o). Assuming $V = V_o = V_b$, equation (5) may be written as

$$qV_o = E_g - q(V_n + V_p) \tag{6}$$

under the turned-on condition of the LED. Since the doping concentrations of the different diodes are expected to be within the same order, the term $(V_n + V_p)$ is virtually a constant quantity. Thus the turn-on voltage is a constant fraction of the band gap. Therefore, equation (6) also predicts, similar to the earlier work (equation (2)), a linear variation of emission frequency with forward turn-on voltage. Correlating the experimentally determined turn-on voltage of the LEDs with their carrier transition energy $h\nu$ calculated from the experimentally measured emission wavelength, a linear relationship is expected if direct carrier transition occurs from the conduction band to the valence band. This work intends to investigate whether such a linear relationship is actually obtained when the two quantities, namely the emission frequency and the turn-on voltage, are measured independently.

3. Experimental set-up

Both the emission and absorption characteristics were studied with five commercially available LEDs of different emission wavelengths, namely blue, green, yellow, red and infrared. The term 'visible LED' is well accepted [7] to denote the LEDs emitting visible radiation and is used throughout in this paper. Two sets of measurements were carried out: one with standard precision instruments and the other with a common spectrometer and grating arrangement. The precision measurements, meant for standardization purposes, are illustrated below.

The emission wavelength peak and bandwidth for each device were precisely measured with an Analytical Spectral Devices FieldSpec UV/VNIR spectroradiometer (325–1075 nm with 1 nm resolution), as listed in table 1. Instead of wavelength (λ), the corresponding frequency ($\nu = c/\lambda$) values were used for graphical representation and calculation.

The absorption wavelength peaks and bandwidths were also accurately measured with the following arrangement. One light beam of a Systronics 2202 dual-beam spectrophotometer (250–1050 nm with 1 nm resolution) was blocked and the LED was exposed to the other beam. The wavelength was varied through the visible and near-infrared regions with 1 nm resolution and the corresponding variation in photocurrent was measured with a picoammeter of resolution 1 pA $\pm$ 0.2%. The measured values are included in table 1.

A second set of data on the emission characteristics of the diodes was procured by measuring the emission wavelengths of the four visible LEDs with a manually operated spectrometer (angular resolution 20 arcsec) consisting of a collimator, grating table and telescope, and grating (600 lines per mm) commonly used in undergraduate laboratories.

Table 1. Experimental emission and absorption parameters of the LEDs.

Colour of LED	Emission wavelength (nm) measured with a spectroradiometer		Absorption wavelength (nm) measured with a spectrophotometer		Turn-on voltage (V)	Emission wavelengths determined with a manual spectrometer	
	Peak	Bandwidth	Peak	Bandwidth		Spectral ranges (nm)	Mean of proper range (nm)
Blue	458	447–466	412	375–425	2.29	434–477 and 495–529	456
Green	562	554–573	552	512–557	1.64	536–545, 559–567 and 574–590	563
Yellow	593	587–601	555	495–578	1.50	568–582, 585–593 and 599–610	589
Red	660	652–668	650	644–655	1.31	613–678	646
Infrared	938	922–956	926	899–941	0.84	–	–

Indeed, the prime target of the investigation was to justify the utility and accuracy of the data obtained by means of this method using the previous data as standard references.

The spectrometer was levelled and focused for parallel rays and the grating was mounted in the usual way. Each of the four visible LEDs was placed one by one under the full-glow condition in front of the collimator slit and the corresponding spectrum was observed at the telescope eye-piece. Recording the angle of diffraction, the wavelength was calculated as usual. It may be noted that an LED is not 'monochromatic' in the true sense. As stated earlier, it emits a continuous spectrum over a certain range of wavelength. At the same time, it does not emit line spectra like common illumination sources, such as sodium, helium or mercury lamps. Consequently coloured patches were seen, instead of sharp lines, under the field of view of the eye-piece. The most intense and prominent regions were selected by the cross-wire and the corresponding diffraction angles were noted. Thus different ranges of emission wavelength were obtained, as shown in table 1.

The turn-on voltages of the five LEDs, as listed in table 1, were estimated from their forward current–voltage characteristics using regulated power supply and digital voltage and current meters. During measurement, it was observed that the visible LEDs were at the just-glowing condition at the turn-on voltage. The radiation from the infrared LED was observed through a digital camera without an IR filter. The current was small, of the order of 1 mA, so the potential drop across the internal series resistance [14] was ignored.

4. Results and discussion

Figure 3 represents the variation of emission frequency peaks measured with the precision spectroradiometer with corresponding cut-in voltages of the LEDs including the infrared one. Obviously the two experimental parameters were measured independently. According to equations (2) and (6), the variation should represent a straight line passing through the origin. But actually that was not found to be so and the data points fitted well with a second-order polynomial, as shown in figure 3.

In fact, there should not be any compulsion for such plots to be linear. If the energy transition of carriers occurred just between the conduction and valence band edges, then the potential barrier, and hence the turn-on voltage, would be a constant fraction of the band gap

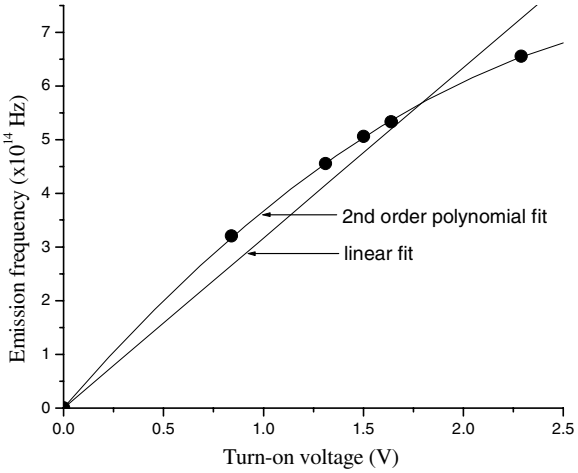

Figure 3. Turn-on voltages of visible and infrared LEDs and the corresponding emission frequencies estimated with a spectroradiometer. Both linear fitting and second-order polynomial fitting of the data points are indicated.

resulting in linear frequency–voltage variation. But in LEDs, often the transition is associated with trap states or recombination states within the band gap created by impurity atoms [7, 8, 14] so that the radiation resulting from such transition possesses lower energy than the corresponding band gap. Precker [16] reported such lowering of energy due to trap states. The change in energy, and hence in emission wavelength, need not be the same for all the LEDs. Thus one cannot explicitly state any functional relationship between the turn-on voltage and the emitted wavelength for a specific LED unless the exact energy level of the recombination centre in that device is known.

Figure 4 shows the variation of the turn-on voltages of visible and infrared LEDs and the corresponding maximum absorption energies. The absorption energy (hc/λ) was calculated for each diode using the absorption wavelength maxima. The energy was expected to correspond to the band gap and involve the band-to-band transition. Consequently, the experimental variation of absorption energy with turn-on voltage should represent a straight line according to equation (6). A similar result was obtained from figure 4 with the y-axis intercept of 0.41 eV.

Comparing the y-axis intercept with the quantity ($V_n + V_p$) and assuming equal amount of doping on the n-side and the p-side, the doping concentration calculated from equation (4*a*) or (4*b*) came out to be of the order of 10^{16} cm^{-3}, a realistic value. Thus figure 4 gives proper information on band gap. Comparing figures 3 and 4 it is understood that the energy positions of the trap centres are such that the emission energy is systematically reduced with respect to the band gap. It may be noted that the absorption wavelengths are in general smaller than the corresponding emission wavelengths, indicating larger energy of absorption. Also, the absorption bandwidths are larger because absorption incorporates a broad energy range of filled and empty states while emission occurs between narrow bands of states [8]. Similar properties are exhibited here.

In addition to the present results, standard data were procured from the literature [8] on the band gap of the LED material and the corresponding emission wavelength, as illustrated in table 2. Nonlinear variation of emission frequency with band gap was found, as shown

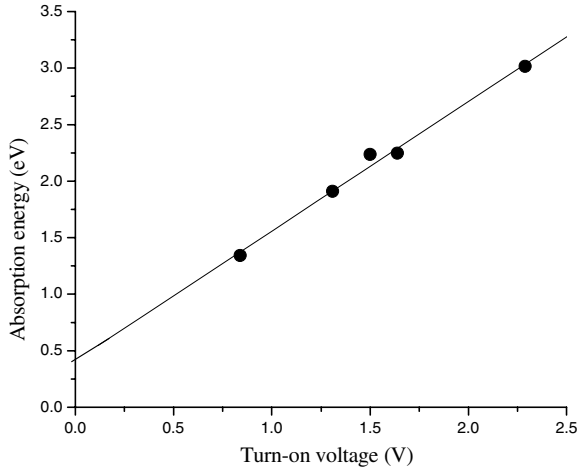

Figure 4. Turn-on voltages of visible and infrared LEDs and the corresponding maximum absorption energies.

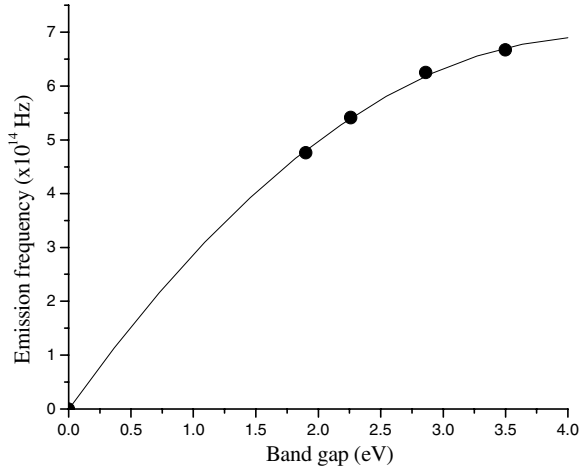

Figure 5. Variation of the band gap of the LED material and the corresponding emission frequency [8].

Table 2. Data for the band gap of the LED material and the corresponding emission frequency [8].

LED material	Band gap (eV)	Emission wavelength (nm)
GaN	3.50	450
SiC	2.86	480
GaP	2.26	555
GaAsP	1.90	630

in figure 5. Such results indicate that the emission wavelength of a LED need not exhibit a linear relationship with turn-on voltage because the trap centres have a trend of modifying the energy of emission. The experimentally available values of emission wavelength and turn-on

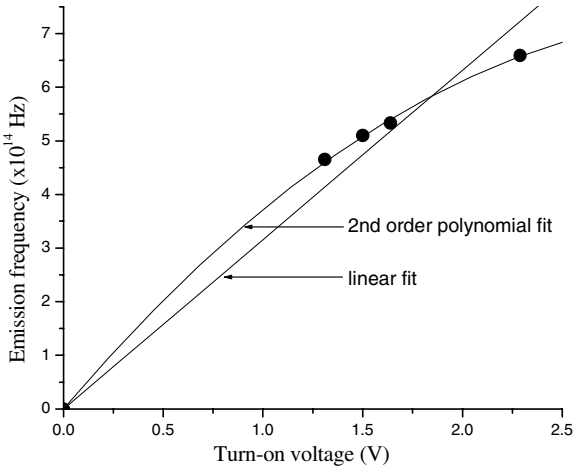

Figure 6. Plot of the turn-on voltages of visible LEDs and the corresponding emission frequencies estimated with a manual spectrometer and grating and determination of the emission wavelength of the infrared LED from the plot. Both linear fitting and second-order polynomial fitting of the data points are indicated.

voltage may not be explicitly related by a functional formula, but are expected to undergo regular variation, which can be fitted with some empirical formula. Only the best fit is to be followed, which need not be a straight line.

Figure 6 shows the plot of the turn-on voltages of the four visible LEDs and their corresponding emission frequencies estimated with the manual spectrometer. The points were fitted with both linear and second-order polynomial curves as shown in the figure. The emission wavelength for the infrared diode was calculated from the fitting curve knowing the turn-on voltage. For linear fit, the wavelength was found to be 1062 nm, far from the standard value of 938 nm obtained with the spectroradiometer (table 1), whereas for polynomial fit, the wavelength was calculated as 934 nm, which was very close to the standard value obtained with the spectroradiometer.

The limitation of measurement with the common manual spectrometer is that it is based on visual observation and cannot be quantified. The broad spectral patch in the field of view can only be averaged over a range. However, such inaccuracy does not disturb the result much. For instance, the red LED exhibited the maximum spread of wavelength which was averaged as 646 nm. Instead, putting the red wavelength = 660 nm and using in figure 6 second-order polynomial fit yielded the infrared wavelength value of 946 nm, still very close to the standard value.

5. Conclusions

This work proposes an easy method of determining the emission wavelength of an infrared LED by measuring the turn-on voltages and corresponding emission wavelengths of several visible LEDs with a common laboratory spectrometer and grating arrangement. The turn-on voltage versus emission frequency graph is extrapolated corresponding to the turn-on voltage of the infrared LED to find the unknown wavelength emitted by it (figure 6). Compared with standard results obtained from precision spectrophotometric and spectroradiometric measurements it is concluded that a manual spectrometer and grating arrangement can more or less accurately

measure the emission wavelength of the infrared LED. It is understood that due to the radiative transitions through traps or recombination centres, the functional relationship between the emission frequency and the turn-on voltage may not be linear or of any explicit functional form. The best possible fitting of the data points in the emission frequency versus turn-on voltage graph for the visible LEDs and extrapolation up to the turn-on voltage of the infrared LED can lead to the emission wavelength of the infrared LED.

Acknowledgment

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