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INTELLIGENT OPTO SENSOR

DESIGNER'S NOTEBOOK

TAOS TEXAS ADVANCED OPTOELECTRONIC SOLUTIONS®

TAOS Photo Sensor Response Part I: Sensitivity to Wavelength

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ABSTRACT

Silicon photodiode response to light is dependent on the wavelength of light incident upon it as well as the temperature of the sensor. This paper will discuss how to calculate the relative response for light sources with varied wavelength composition or spectra.

RESPONSIVITY

Optical sensors exhibit a transfer function of an electrical output for a given optical input. This electrical output is a function of the response of the sensor for a given light energy. Silicon optical detectors are generally more sensitive to some wavelengths of light than others, thus the sensor's responsivity is wavelength dependent. This relationship is shown in spectral responsivity charts, as is shown in Figure 1.

A light source's energy output varies with wavelength. For instance, the optical power in a green LED will be concentrated around 525 nm while the optical power in a red LED may be concentrated around 640 nm. The concentration of optical power at different wavelengths for a given light source is called the source's Spectral Power Distribution (SPD).

The spectral responsivity charts in TAOS datasheets are normalized at 100% to a specific wavelength of light. Certain quantities, such as the response of the sensor are given in relation to this normalized figure. Often it is useful to scale the response to a light source with a peak wavelength different than the one that the spectral responsivity chart is normalized to. The following examples will step through this scaling process.

The examples discussed in this paper use the TSL230RD Light-to-Frequency converter as the light sensor. The same analysis can be made using TAOS Light-to-Voltage sensors, and Light-to-Digital sensors. The only difference would be the format of the absolute response.

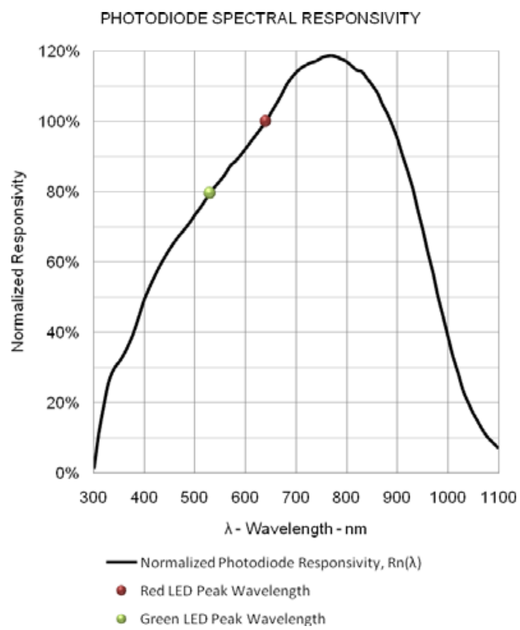

Figure 1. Normalized Spectral Responsivity

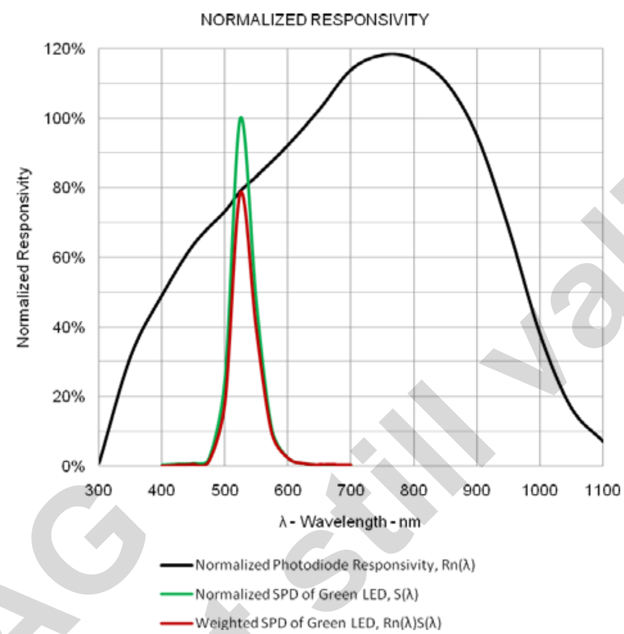

Figure 2. Normalized SPD of Green LED

Graphical Method

Assume that we are interested in determining the expected output frequency for a green LED with a peak wavelength of 525 nm. From Figure 1, we can see that the sensor's normalized response (R_n) at 525 nm (green dot) is about 80% of its response at 640 nm (red dot), which is the 100% normalized reference point. Therefore, if we expect an absolute response of 790 Hz/(μW/cm^2) at 640 nm, we can expect 632 Hz/(μW/cm^2) at 525 nm.

The preceding example assumes that our optical input is monochromatic (narrowly concentrated spectrally) at 525 nm. For many colored LED light sources, this approximation can be made.

Numerical Method

Since a broadband input is not monochromatic, it cannot be approximated at a single wavelength. This makes the graphical method impractical, and the numerical method better suited for broadband light sources.

In using the numerical method, we must integrate the product of the source's SPD and the sensor's responsivity. Since the sensor's responsivity is the result of measured data, we must approximate this process by summing the product of the sensor's responsivity with the spectral components of our source at all wavelengths of interest. This gives us the SPD of the broadband source weighted to the responsivity of the sensor at a known monochromatic source. The ratio of this weighted SPD to the source's original SPD will equal the ratio of the absolute broadband response to the known absolute monochromatic response. This relationship is shown in Equations 1 and 2.

$$\text{Scaling Factor} = \frac{\sum R_n(\lambda)S(\lambda)}{\sum S(\lambda)} \qquad \text{(Eq. 1)}$$

$$\text{Calculated Response} = \text{Scaling Factor} \times R_e \qquad \text{(Eq. 2)}$$

Where $R_n(\lambda)$ is the normalized spectral responsivity of the photodiode, and $S(\lambda)$ is the SPD of the optical source at a particular wavelength (λ). R_e is the absolute response of the photodiode at a known wavelength. This is the absolute response at the wavelength where the normalized response is 100% (i.e. the red dot in Figure 1). This value will be listed in the electrical specifications of the datasheet.

This process will be shown with an example. Let's revisit the first example and determine numerically the expected response for a green LED. Figure 2 shows the spectral responsivity of the sensor along with the normalized SPD of the green LED.

The red line in Figure 2 represents the product of the source's SPD with the spectral responsivity of the sensor, or $R_n(\lambda)S(\lambda)$. The ratio of the summation of this curve with the summation of the source's SPD will return a scaling factor that can be used in Equation 2 to determine the absolute response. Table 1 includes the numerical data from Figure 2 in 25 nm increments.

Table 1: Spectral Data for Green LED Example

Wavelength (nm)	**Normalized Photodiode Responsivity, $R_e(\lambda)$**	**Normalized SPD, $S(\lambda)$**	**Weighted SPD, $Re(\lambda)S(\lambda)$**
400	49.1%	0.4%	0.2%
425	57.4%	0.5%	0.3%
450	63.8%	0.7%	0.5%
475	68.6%	2.0%	1.4%
500	73.4%	25.1%	18.4%
525	78.6%	100.0%	78.6%
550	83.3%	46.8%	39.0%
575	88.1%	10.7%	9.4%
600	92.4%	2.4%	2.3%
625	97.0%	0.8%	0.8%
650	102.6%	0.5%	0.5%
675	108.9%	0.4%	0.4%
700	113.9%	0.3%	0.3%
		190.5%	**152.0%**

Using Equation 1,

$$\text{Scaling Factor} = \frac{\sum R_n(\lambda)S(\lambda)}{\sum S(\lambda)} = \frac{152.0\%}{190.5\%} = 79.8\%$$

From Equation 2, we can expect the response from a green LED to be 79.8% of the absolute response from a red LED at 640 nm. For this example, the absolute response, R_e is 790 Hz/(μW/cm^2) at 640 nm. Therefore we can expect a broadband response of 630.42 Hz/(μW/cm^2). Note that this is very close to 632 Hz/(μW/cm^2), the approximate response of the green LED with a 525 nm peak wavelength obtained using the graphical method.

It is often desirable to measure the response of broadband light sources that are often encountered in everyday life, such as fluorescent bulbs, incandescent bulbs and sunlight. A good example of a broadband light source is a 3000K blackbody light source, which is similar to a halogen bulb. The SPD of the 3000K source is shown in Figure 3 along with the normalized responsivity of the sensor. The product of these two curves is also shown in the figure as the weighted SPD of the source. The numerical data from Figure 3 is shown in Table 2.

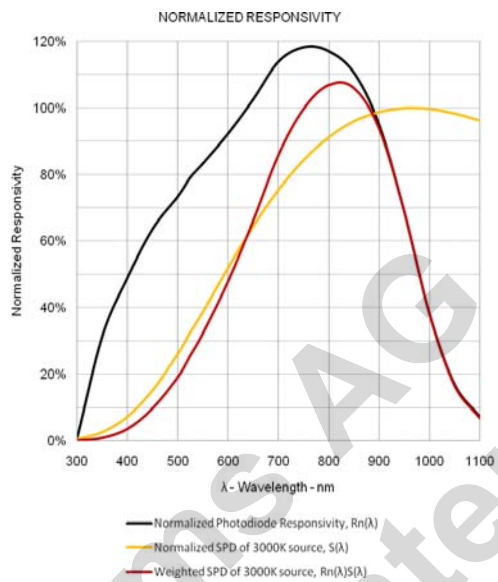

Figure 3. Normalized SPD of 3000K Source

Table 2: Spectral Data for 3000K Source Example

Wavelength (nm)	Normalized Photodiode Responsivity, $R_e(\lambda)$	Normalized SPD, $S(\lambda)$	Weighted SPD, $Re(\lambda)S(\lambda)$
300	1.1%	0.6%	0.0%
350	31.7%	2.6%	0.8%
400	49.1%	7.3%	3.6%
450	63.8%	15.3%	9.7%
500	73.4%	26.1%	19.2%
525	79.0%	32.5%	25.7%
550	83.3%	38.8%	32.4%
600	92.4%	52.0%	48.0%
650	102.6%	64.5%	66.2%
700	113.9%	75.4%	85.9%
750	118.2%	84.4%	99.8%
800	117.1%	91.2%	106.8%
850	110.5%	95.9%	106.0%
900	95.1%	98.8%	93.9%
950	68.9%	99.9%	68.9%
1000	38.4%	99.7%	38.3%
1050	16.9%	98.4%	16.7%
1100	7.0%	96.2%	6.8%
		1079.5%	**828.5%**

Using Equation 1,

$$\text{Scaling Factor} = \frac{\sum R_n(\lambda)S(\lambda)}{\sum S(\lambda)} = \frac{828.5\%}{1079.5\%} = 76.7\%$$

Thus from Equation 2, we can expect our broadband response to be 76.7% of our absolute response, R_e. This gives us a response of 605.93 Hz/(μW/cm^2).

ACCURACY

The examples used in this document relied on data sampled at some incremental wavelength. As the increment is shortened, more sampling data can be calculated resulting in a more accurate calculation. The inaccuracy caused by not using enough sampling points can be especially problematic when the light source of interest has one or more narrow peaks, such as a fluorescent source. These peaks could easily be skipped if the wrong sample wavelengths are used. To achieve sufficient accuracy, appropriately sampled SPD information will need to be obtained.

The Commission Internationale de l'Eclairage (CIE) has defined many standard illuminants that are commonly found. Normalized SPD information for these illuminants can be found in many resources including Daniel Malacara's *Color Vision and Colorimetry Theory and Applications*. A good place to acquire graphical SPD information for many light sources and standard illuminants is the General Electric website. Although external data can be useful, small subtleties might be present in any light source that can lead to inaccuracies. The only true way to characterize source illumination is through empirical data.

CONCLUSION

It is often important to know when using a TAOS optical sensor, what electronic response to expect for a given optical input. This response is a factor of the sensor's spectral responsivity, which varies with wavelength. The response information is presented in TAOS datasheets normalized to a specific wavelength. The examples in this document step through the process of scaling the response from a known monochromatic source. This process will allow one to calculate the expected response for any known light source, thus giving a more complete view of how TAOS photosensors can be integrated into any application.

Part II of this paper focuses on how TAOS photo sensors are sensitive to changes in temperature. It details how the responsivity curve is altered at a given temperature. For more general information on TAOS optical sensors, please visit http://www.taosinc.com/.

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