An Optical Source for Characterizing CMOS Imagers: Characterization and Calibration Results

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Abstract

Characterizing the optical properties of CMOS imagers requires a source of illumination. This paper presents the characterization and calibration of an optical source which consists of an array of light emitting diodes, an infrared cut-off filter, and diffusing lenses– all of which are encased in an anodized aluminium housing. The characterization and calibration results of the optical source are presented in detail. The optical source is capable of illuminating a 15 mm field at a conjugate distance of 50 mm with 98 percent uniformity. The spatial uniformity of the source is compared with with an integrating sphere an Optoliner projection system. From the characterization and comparison results, it is concluded that the optical source system is capable of characterizing CMOS imagers.

1 Introduction

The pixel array is the core of the CMOS image sensor. It is a 2-dimensional array that converts the incident light into electrical signals and is directly responsible for the image quality of the camera system. Foundries that manufacture CMOS imagers are responsible for ensuring the optical quality of each sensor array. To characterize the optical performance of the imager, a light source is used to illuminate the pixel array and an image is acquired.

The optical source that has been designed to characterize CMOS imagers consists of an array of light emitting diodes (LED), an infrared (IR) cut-off filter, and diffusing optics. LEDs are chosen as the source of optical radiation because of their relative narrow bandwidth, fast rise/fall times, compact form, and ease of control. The led array and optics are configured into a single illuminator unit. Figure 1 shows how the illuminator components are assembled.

As shown in fig. 1, the LED array is placed in the back of the mechanical housing. Following the LED
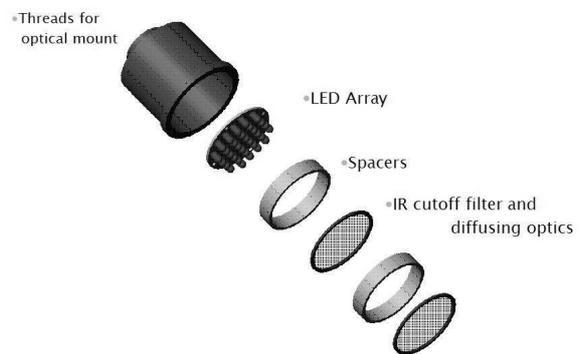

Figure 1: Exploded view of the illuminator system.

array, spacers are inserted into the barrel of the light source in order to separate the LED ring from the IR cut-off filter. Then, additional spacers are placed between the IR cut-off filter and the diffusing optics. The spacers are made of nylon and can easily be cut to the appropriate length. The complete illuminator system is held in place by a retaining ring fastened at the end of the barrel of the mechanical housing. The intensity of the radiated light is electronically controlled through a DC electronic driver circuit, this enables the user to set the intensity of the irradiance on the device under test as a function of the current through the LEDs.

2 Characterization and Calibration

The characterization and calibration results of the optical source system will demonstrate the capabilities of the source system design. The characterization plan is a detailed set of tests designed to characterize the optical performance of the light source. The plan is intended to measure the illuminator system's ability to meet the optical specifications outlined in the pre-

vious chapters. After the characterization plan, the calibration procedure is implemented to measure the irradiance at the device under test and relate the irradiance to the input current of the illuminator.

Before making any light measurements, a systematic approach to defining the quantity of light must first be established. The specific optical concepts and definitions that are best suited for this application are presented in this section. The energy in joules (Q) of a photon of light is related to its frequency and wavelength by the following definition:

$$Q = hv = \frac{hc}{\lambda}, \tag{1}$$

where h is Planck's constant, v is the frequency, λ is the wavelength, and c is the speed of light. The optical power (ϕ) is a measure of the energy flow of light in joules per unit time (Q/t), and is expressed in watts. Optical power is often described as a measure of the radiant flux leaving a source and passing through a reference surface (A) [1]. If the surface (A) is positioned a distance (R) from the radiating source of light (see fig. 2), the illumination at that surface is given by the irradiance (E), or radiant flux per unit area given by:

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

Because the optical source is intended to illuminate a CMOS imager at a fixed distance (R), the units of irradiance in W/cm^2 will be used to express the level of illumination at the device under test [2]. In the next
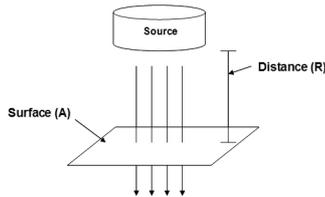

Figure 2: A surface (A) positioned a distance (R) from a radiating source of light.

section a characterization plan is presented followed by the characterization of the spectral radiance and the uniformity of illumination at the device under test. To conclude the section, the calibration of the optical source is presented in terms of the absolute irradiance at the device under test to the magnitude of the DC current through the illuminator LEDs.

3 Characterization Plan

In order to use the optical source to characterize the performance of CMOS image sensors, the spectrum of the emitted light must be known and the pixel must be uniformly illuminated.

3.1 Spectral Irradiance

The optical source is capable of emitting three distinct colors of light: red, green, and blue. It is important to characterize the emission spectrum of the optical source. Characterizing the spectrum reveals the spectral location where peak radiant power occurs. The optical source was connected to a monochromator and a calibrated radiometer to characterize the emission spectrum and find the spectral peak. These optical instruments (made by Oriel Instuments) are commercially available. Figure 3 illustrates the optical bench setup used to measure the spectral emission of the light source.

Figure 3: Instrumentation setup for characterizing the emission spectrum.

A monochromator is an optical instrument that uses specialized optics to separate light into its spectral density function. As seen in fig. **??** in chapter 3, the LEDs have a narrow band emission. Each individual band in the emission spectrum of the optical source can be characterized separately by directing the light from the optical source to the monochromator. After selecting a particular wavelength increment, the monochromator directs the light to illuminate the calibrated radiometer. The Oriel radiometer is a photodiode that has been calibrated using international standards to determine the irradiance imposed on the photodiode versus wavelength. The wavelength of light where the peak emission occurs can be found by recording the irradiance at each incremental band in the LED emission spectrum. Figures 4, 5, and 6 show the spectral radiance of the optical source for each color red, green, and blue, respectively.

The radiant spectral peak of the red light occurs at a wavelength of 620 nm, the green light peak occurs at 525 nm, and the blue light peak occurs at 455nm. The half power emission bandwidths are 30 nm for red, 40 nm for green, and 15 nm for blue, respectively.
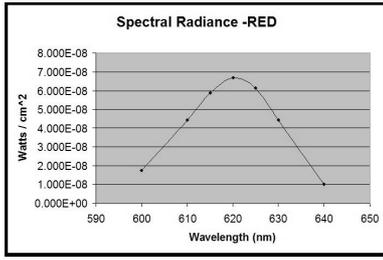
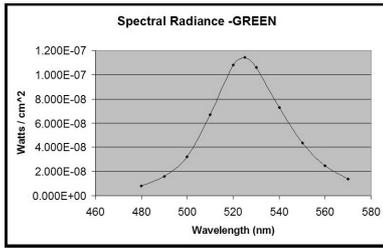Figure 4: Red emission spectrum of the optical source.

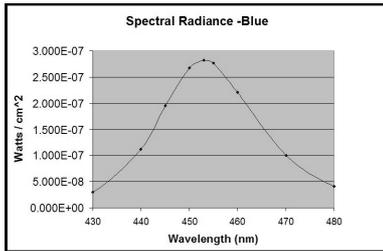Figure 5: Green emission spectrum of the optical source.

Figure 6: Blue emission spectrum of the optical source.

3.2 Characterized Field of Illumination

A CMOS imager or another type of device under test is placed in the illuminated field of the optical source. The illuminated field, or scene, should be characterized in terms of spatial location for correct placement of a device under test. Characterizing the field of illumination created by the light source requires measuring the irradiance at distributed spatial locations in the illuminated scene.

A calibrated photodiode is placed on a surface normal to the projection of light from the source. Using a gimbal mount, the calibrated photodiode is moved in 1 mm increments across the illuminated scene. The photodiode is passed through the optical axis (the spatial location directly beneath the center of the radiating

source). Figure 7 shows the plot of the normalized irradiance across an illuminated scene of 15 mm.
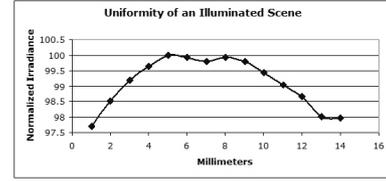

Figure 7: Normalized irradiance across a 15-mm illuminated scene centered on the optical axis of the source.

From the data it is concluded that the spatial locations of peak irradiance surround the optical axis. More importantly, it can be concluded that across an illuminated scene of 15 mm, the irradiance is within 2 percent of the maximum. In other words, if an illuminated scene with a diameter of 15 mm is centered on the optical axis, it will have a non-uniformity of 2 percent. This measurement holds true for all three colors red, green, and blue. The results are only valid if the illuminated scene is at a conjugate distance ranging from 50 to 75 mm.

In order to characterize the irradiant uniformity across a larger surface area, the photodiode was placed directly on the optical axis and then spatially displaced 15 mm away from the optical axis. Figure 8 shows the irradiance measured in 1-mm displacements away from the optical axis of the source. The plot demonstrates that a 30-mm diameter surface centered on the optical axis will have a uniformity of approximately 95 percent.
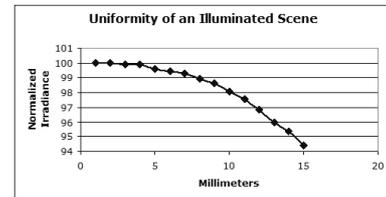

Figure 8: Normalized irradiance across a 15-mm illuminated scene away from the optical axis of the source.

The measurements in fig. 8 were made moving away from the optical axis of the source in numerous directions. The irradiance decreases as a function of distance from the optical source equally in all directions.

It was concluded that the irradiance of the source has a circular pattern. Using these measurements, a map is made to characterize the field of illumination created by the optical source. Figure 9 is an imprecise characterization map of the optical source's illuminated field. Such a map can be used by an operator when placing an imager under test. The characterization map is valid when the optical source is used at a conjugate distance between 50 and 75 mm. From the data it is concluded that using high-angle diffusing optics and placing LEDs in a strategic array, a uniform distribution of light can be created. The uniformity of the optical source is compared with commercially available light sources in the next chapter.
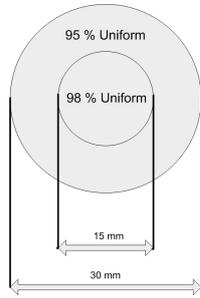

Figure 9: The optical source's characterized field of illumination.

4 Calibration Procedure

The optical source calibration is intended to compare the irradiant intensity of the optical source at the device under test with the input current of the LEDs in the illuminator. Calibrating the optical source in terms of current is necessary in order to adjust the current source to supply the proper amount of current to the illuminator. To calibrate the optical source, the irradiance was measured by a CMOS image sensor at conjugate distances of 50, 67.5, and 75 mm. The sensitivity of the CMOS imager was calibrated in terms of volts per energy flux density. The flux density is denoted uJ/cm^2 and can be computed by knowing the size of the pixels in the CMOS imager array. Figure 10 shows the sensitivity of the calibrated CMOS imager as a function of wavelength.

After exposing the CMOS pixel array to the incident radiation from the light source for a specified amount of time (integration time), the image sensor output is recorded. The CMOS image sensor output voltage is then converted to irradiance by dividing the
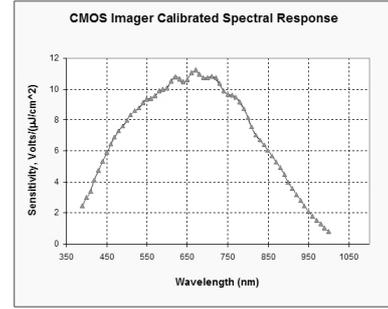

Figure 10: Sensitivity of the calibrated CMOS imager.

output voltage of the imager by the appropriate sensitivity value and the integration time. The following equation gives the conversion:

$$\frac{Vcmos}{V/(uJ/cm^2)\cdot\delta t} = \frac{uJ}{cm^2\cdot\delta t} = \frac{W}{cm^2} = E, \quad (3)$$

where $Vcmos$ is the CMOS image sensor output voltage, δt is the integration time, and uJ/cm^2 is the calibrated sensitivity value taken from fig. 10. Using this procedure, the light source output at any conjugate distance can be computed in terms of input current.

Figures 11, 12, and 13 are plots of the irradiance at three different conjugate distances as a function of LED current. Each plot gives the irradiance at the device under test for the colors red, green, and blue, respectively. The conjugate distances 50, 67.5, and 75 mm were chosen for the test. These dimensions are according to the physical dimensions of the intended application. The sensitivity value from fig. 10 was used to convert the output voltage of the calibrated CMOS imager to irradiance. Recalling from the previous section, the peak spectral radiance of the optical source occurs at the following wavelengths: 620 nm for red, 525 nm for green, and 455 nm for blue.
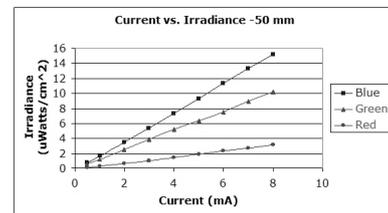

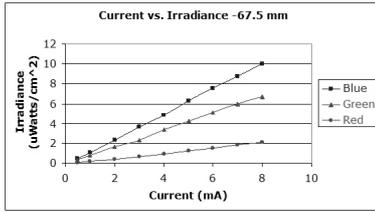Figure 11: Current vs. Irradiance at a conjugate distance of 50 mm.

Figure 12: Current vs. Irradiance at a conjugate distance of 67.5 mm.
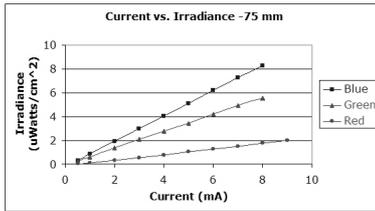

Figure 13: Current vs. Irradiance at a conjugate distance of 75 mm.

The calibration plots indicate a linear relationship between the irradiance and the LED current. The small amount of nonlinearity seen occurs because of the inherent electro-optical performance of the LEDs in the illuminator. It is also noted that any nonlinear relationship between irradiance and current is compensated for in the complete optical source system because of the feedback correction achieved by using the TSL253 light-to-voltage converting sensor.

The data in fig. 14 was taken in order to calculate the amount of current that is required to sufficiently illuminate a CMOS imager. The voltage output of the pixel array is a function of the integration time, conjugate distance, and irradiance upon the array. The irradiation is controlled by the light source and the conjugate distance is controlled by the physical test configuration. However, the integration time of the sensor is a function of the device being tested. The integration time is usually programmable and is able to be controlled within a given range depending on the specific type of CMOS imager. For the following experiment, a color CMOS image sensor was configured at a conjugate distance from the device under test of 75 mm and the pixel array integration time was chosen to be 20 ms. The color CMOS image sensor was then illuminated by the optical source using the colors red, green, and blue. The curves in fig. 14 demonstrate the responsivity of the red, green, and blue pixels when illuminated with their corresponding colors.
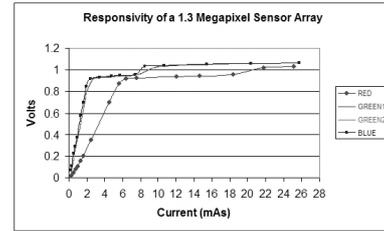

Figure 14: Current required to saturate a 1.3 megapixel CMOS imager.

It is concluded from fig. 14 that at a conjugate distance of 75 mm and an integration time of 20 ms, the pixel array is saturated at currents much less than 20 mAs or 4 uW/cm^2 of red light. Because the maximum current capacity of the illuminator unit is 900 mAs, the optical source is capable of providing much more irradiance than necessary when configured at a conjugate distance of 75 mm. This provides freedom of adjusting the conjugate distance to a much greater value and/or shortening the integration time on the device under test. This capability becomes valuable for the characterization engineer because it enables the optical source to be used with custom device characterization procedures and in nearly all desirable configurations.

5 Performance Comparison

From the test results given in the previous section, it is concluded that the illuminator is a source of sufficiently uniform illumination to characterize a CMOS imaging array. In this section, a direct comparison is made between the irradiant uniformity of the optical source and two commercially available state of the art illuminators. The uniformity of the optical source is compared with that of an integrating sphere and an Optoliner Projector.

6 Comparison with an Integrating Sphere

An integrating sphere is known as a near ideal source of uniform illumination; it is most often used for radiometric measurements when uniformity of light is essential. An integrating sphere is a hollow sphere coated on the inside with a highly reflective white diffuse material [3]. Figure 15 illustrates the operating principle of an integrating sphere [4]. Light is collected in the sphere through an input port and is then reflected and scattered by the sphere's inner surface.

The light then exits through an output port as an almost ideal uniform beam of light. As can be seen in fig. 15, a baffle is inserted inside the sphere to prevent any direct ray paths from the input port to the output port.

Comparing the irradiant uniformity of the optical source to that of an integrating sphere is used to set a standard of performance for the optical source design. The comparison also verifies the accuracy of the characterization data presented. The following experiment was conducted to compare the irradiant uniformity of the two sources. Each source individually illuminated a 1.3 megapixel CMOS image sensor that has an active imaging area of 6.83 by 5.45 mm [5]. The CMOS pixel array was spatially centered on the optical axis of the source and was configured at a conjugate distance of 75 mm. Each test was carefully configured to be identical in order to provide a valid comparison between the two distinct sources. While under direct illumination from an individual source, an image was captured and each individual pixel value was recorded. The pixel values from each image were then plotted in a histogram. Figure 16 contains the histograms of the CMOS imager array pixel values.

The plot labelled "Optical Source" is a histogram of the imager pixel values when illuminated by the LED optical source. The plot labelled "Integrating Sphere" is a histogram of the imager pixel values when illuminated by the integrating sphere. Using the same CMOS imager, and configuring the experiments exactly the same, a useful comparison of the histogram plots is made. Because each histogram is a distribution of all 1.3 million pixel values in the imager array, a more narrow distribution of pixel values signifies a more uniform irradiance across the array. As can be seen from the histograms in fig. 16, the imager array pixel values have a more narrow distribution when il-
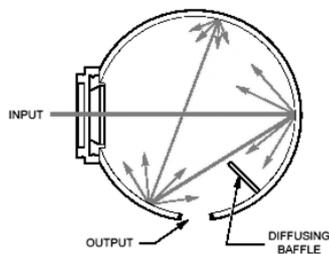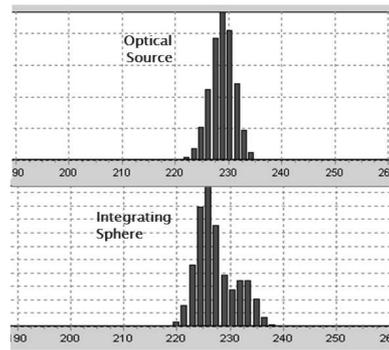

Figure 16: Histogram plots used to compare the irradiant uniformity of the LED optical source with an integrating sphere.

luminated by the optical source. It is noted that the CMOS imager used in the experiment has an associated FPN and the spatial non-uniformity of the two distinct light sources is not identical. The imager FPN and different spatial non-uniformity of the sources are possible reasons why the LED optical source appears to illuminate the CMOS imager more uniformly.

The following statement is concluded from this experiment. At a conjugate distance of 75 mm, the LED optical source illuminates this particular 1.3 megapixel CMOS imager array more uniformly than an integrating sphere. The experimental results indicate that the uniformity of the LED optical source is comparable to that of an integrating sphere.

7 Comparison with an Optoliner Projector

The Optoliner projector made by Davidson Optronics is another commercially available optical source used to characterize the performance of CMOS image sensors. As shown in fig. 17, the Optoliner projector is an illumination system that utilizes an incandescent bulb, an integrating sphere, and lens projection optics [6].

An Optoliner Projector is used to project

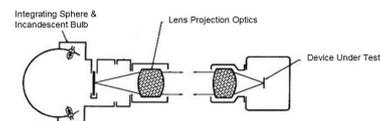Figure 15: Principle of operation of an optical integrating sphere.

Figure 17: Davidson Optoliner Projector System.

distortion-free images on image sensor arrays and to illuminate sensor arrays with a high degree of uniformity. The Optoliner Projector serves as a good measure of comparison with the LED optical source because it is a widely used imaging instrument. In order to compare the irradiant uniformity of the Optoliner Projector with the LED optical source, each experiment was configured identically. A calibrated photodiode was placed on a surface normal to the projected beam of light at a conjugate distance of 75 mm. Using a gimbal mount, the calibrated photodiode was moved in increments of 1 mm across an illuminated scene passing through the optical axis. The irradiance detected at each 1-mm displacement was detected and plotted in fig. 18.

Shown in fig. 18, the optical source illuminates a 15-mm diameter scene centered on the optical axis with a uniformity of 98 percent. The plot shows that the irradiance of the Optoliner Projector across a 15-mm field centered on the optical axis has a uniformity of approximately 90 percent. The LED optical source has a more uniform irradiance than the Optoliner Projector System.

8 Conclusions and Future Research

From the characterization data, it has been concluded that the design of the optical source has met the outlined performance requirements. The wavelength of the light radiated from the LED optical source was characterized, thus revealing the emission spectrum of the source. The irradiant uniformity of a 15 mm diameter illuminated scene was characterized and found to be 98 percent uniform. An illuminated scene with a 30 mm diameter was also characterized and found to be 95 percent uniform. The irradiant uniformity of the LED optical source was compared with an integrating sphere and an Optoliner Projector. The experimental results indicated that the irradiant uniformity of the LED optical source is comparable
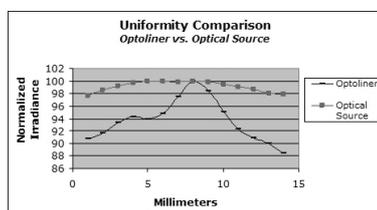

Figure 18: The irradiant uniformity of the LED optical source compared with the irradiant uniformity of the Optoliner Projector.

to an integrating sphere. It was also concluded that the irradiant uniformity of the LED optical source was found to be superior to that of an Optoliner Projector. From the characterization and comparison results, it is concluded that the proposed optical source meets the necessary specifications for characterizing CMOS imagers.

The optical source might also be characterized and calibrated under differing environmental conditions. CMOS imagers are often tested for functionality at extreme temperatures. One may consider characterizing the spectral emission and field of illumination of the LED source when it is operated at extremely high and low temperatures. The optical source may also be considered as an appropriate source of irradiance when testing and characterizing other optoelectronic devices. The optical source could possibly be used to characterize and/or calibrate photo cells, CCDs, radiometers, etc. More characterization may be necessary as the optical source system is used in an increasing number of applications.

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