Spectral Power and Irradiance Measurements of Retinal Projection Displays

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ABSTRACT

Several optical metrology considerations are demonstrated in measuring the spectral power and irradiance of laser-based of retinal projection displays. These measurements determine important safety and performance characteristics.

1. INTRODUCTION

The development of near-eye displays (NEDs) requires optical methods and instruments that can properly evaluate the performance of these systems. Previous work demonstrated that instruments used for direct view displays may not be appropriate for NED measurements.[1,2] The measurement instruments and methods need to mimic the optical configuration and motion of the human eye more closely. The introduction of retinal projection displays has further expanded the application areas for NEDs.[3] The example shown in Figure 1 illustrates a typical implementation of a retinal projection device, where the virtual image is created by raster scanning red, green, and blue laser beams over an area of the retina. This technology offers some advantages, such as focus free viewing, that are difficult to achieve through more traditional NED approaches.[4] But it also created additional requirements on the measurement instruments.[5] Even so, for many of the typical NED visual performance characteristics, the same NED measurement methods can be applied in evaluating the virtual image.

Instead of measuring the virtual image characteristics directly, some manufacturers evaluate the retinal projection display performance by measuring its spectral irradiance at the image plane (the plane simulating the position of the retina behind the device focal point, see Fig. 1).[4] This can be a useful way to determine the device color, and estimate the perceived virtual image luminance. However, the narrow spectrum of the laser sources needs to be carefully considered. Spectral stray light can be a significant effect for laser sources.[6] This paper investigates the impact of spectral stray light for retinal projection color measurements at the image plane.

The use of laser sources to scan the back of the retina also creates safety concerns that must be evaluated for each retinal projection system. Excessive laser power can damage the eye or skin.[7] In addition, the measured laser power from a retinal projection device is used by regulators to determine how it is classified as laser product.[8] Given the importance of these power measurements, this paper also investigates the necessary instrument requirements for measuring spectral radiant flux from retinal projection displays.

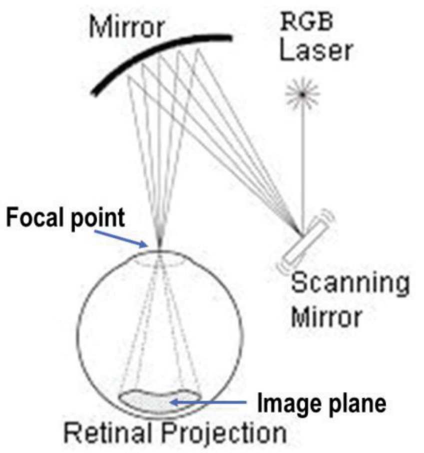

Fig. 1 Example configuration setup of a retinal projection device.

2. MEASURING SPECTRAL RADIANT FLUX

Laser power measurements at low power levels are commonly made using photodiode-based sensors. The wavelength of the light must be known to properly set the calibration of the sensor. These laser power meters typically assume that the laser is at normal incidence to the sensor to avoid any dependence on polarization or incident angle/beam divergence. Therefore, because of this polarization and incident angle dependence, the simple photodiode-based laser power meter may not be appropriate for retinal projection devices due to the angular scanning of the laser beam (see Fig. 1).

A robust way to minimize the dependence of laser polarization and inclination angle is to scramble the input beam using an integrating sphere. The light in the sphere can then be measured by a spectroradiometer or photodiode sensor. For single wavelength laser sources, the choice of detector should make little difference. However, for these retinal projection displays, using a spectroradiometer can give significantly more accurate results.

The value of using an integrating sphere with a spectroradiometer for retinal projection laser power measurements was demonstrated by characterizing a commercially available color retinal projection device (see Fig. 1). The 4 mm diameter measurement port a 2” diameter PTFE integrating sphere was centered at the focal point of retinal projection device, ensuring that all of the laser power entered the sphere. The spectral radiant flux in the sphere was measured by a spectroradiometer with a 5 nm bandwidth. The sphere+spectroradiometer light measuring device (LMD) was calibrated for flux using a spectral irradiance source traceable to NIST. Unless stated otherwise, the reported results also include a spectral stray light correction applied during the calibration of the LMD.[6] Example spectra of the white, red, green, and blue colors, measured at maximum full screen signal, for the retinal projection device are given in Fig. 2.

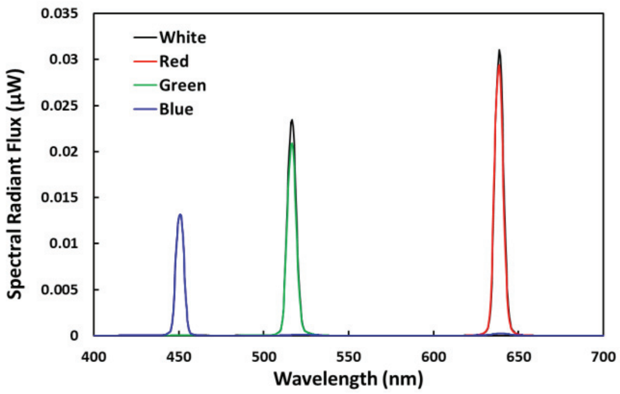

Fig. 2 Example white, red, green, and blue spectral radiant flux of commercial retinal projection device.

Although it is a bit difficult to see in the figure, the white spectra is not completely additive (W≠R+G+B). In this case, the flux value of white at each spectral peak was different by up to 12 % from the peak flux value of a single rendered color. As a consequence, the laser spectral radiant flux cannot be obtained by simply measuring the red, green, and blue spectra separately and then adding them up to get the white spectra. A device that is not additive means that a simple photodiode-based measurement of radiant flux cannot be used to measure colors with mixed primaries (like white) because the individual colors do not add up accurately.

The spectral radiant flux of the individual primaries plotted on a log scale is given in Fig. 3. From the log plot, we can see that although a single primary color was rendered, the device still leaks power from the other primaries. Table 1 indicates how much additional flux is contained in the leakage from the other primaries. For the device under test, when a blue full screen was rendered as maximum signal level, an additional 7.2 % radiant flux was leaking into the spectrum from the red and green lasers. If the luminous flux was considered, the percent would be substantially higher (65 %) for blue. If a spectral measurement had not been performed, then it would have been difficult to notice the contribution from the leaked flux. That would be the situation for simple photodiode-based flux measurements. In those type of laser power meters, the instrument typically assumes that all the flux is from a single wavelength. Therefore, these instruments would overestimate the flux of a given primary color in the common situation of emission leakage from other primaries, such as shown in Fig. 3.

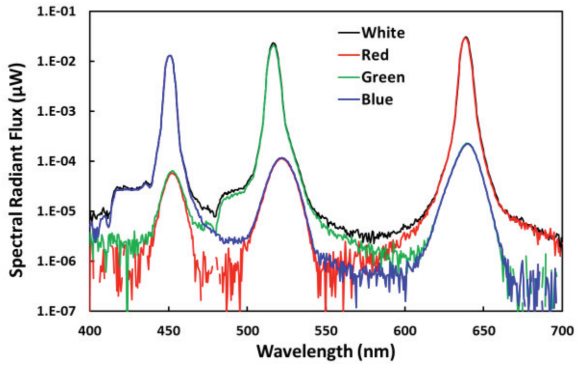

Fig. 3 Log scale plot of example data in Fig. 2.

Table 1 Spectral Radiant Flux Leakage

	Percent increase from leakage		
Primary	Red	Green	Blue
Radiant flux	1.6 %	2.9 %	7.2 %
Luminous flux	3.9 %	0.8 %	65 %

3. MEASURING SPECTRAL IRRIANCE

The spectral irradiance from the commercial retinal projection display was measured by moving the same sphere+spectroradiometer LMD back to the idea image plane (see Fig. 1). If the focal point is at the nominal position of the lens in the human eye, the effective focal length of the eye would put the image plane at about 17 mm behind the focal point. For the retinal projection device used in this study, the illumination pattern at that distance substantially overfilled the 4 mm diameter measurement port of the LMD’s integrating sphere, as is necessary for a proper measurement. The measurement port was centered within the illumination pattern projected by the device. As mentioned previously, the illuminance measured by this method can be used to indirectly estimate the perceived luminance of the virtual image. However, this study focuses on the color information obtained by these measurements.

The spectral distribution measured at the center of the illumination pattern projected by the device was similar to the spectra shown in Fig. 2. A colorimetric analysis of the measured spectral distribution can be used to determine the CIE 1931 chromaticity coordinates for all colors. A similar analysis could also be performed on the spectral radiant flux data. However, light from the flux measurement spectrally integrates all the color nonuniformities over the entire virtual image. Whereas the center spectral irradiance measurement should represent the chromaticity in the center of the virtual image.

It is known from previous work that spectral stray light can impact the measurement of narrow band spectral sources like lasers. In this study, we investigated the influence of spectral stray light on the spectral irradiance measurement. A method to minimize spectral stray light for array spectroradiometers was developed by Zong.[6] The LMD used in this study was calibrated with and without a spectral stray light correction.

Figures 4 to 6 show the center spectral irradiance of the retinal projection device for the full screen red, green, and blue colors at maximum signal with and without spectral stray light correction. For this device spectra, it is clear from the figures that the spectral stray light correction reduced the stray light near the peak emission by about half an order of magnitude. The spectral leakage from the other primary colors is also observed, similar to what was seen in the flux measurements in Fig. 3.

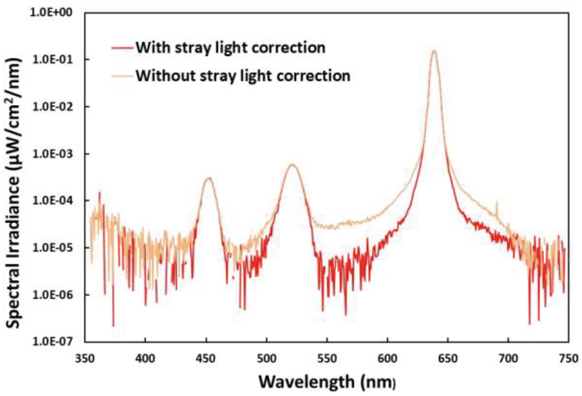

Fig. 4 Log scale spectral irradiance of red with and with spectral stray light correction.

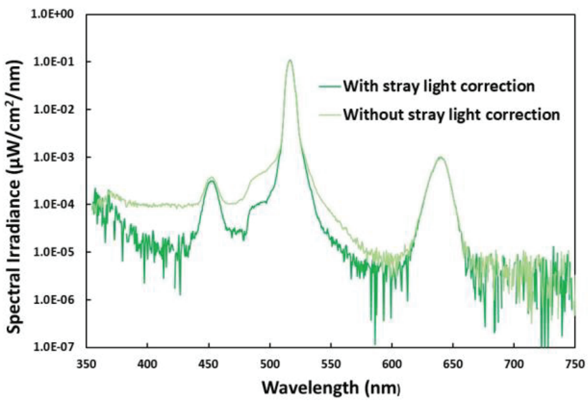

Fig. 5 Log scale spectral irradiance of green with and with spectral stray light correction.

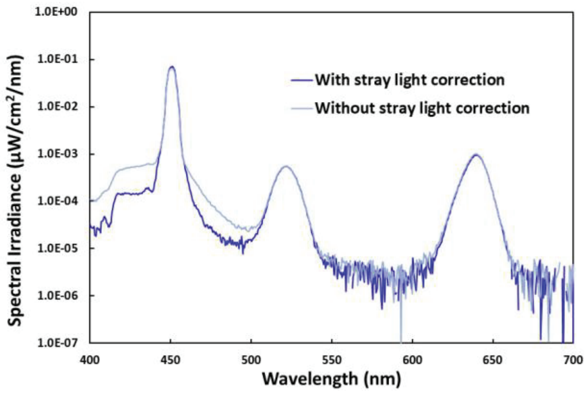

Fig. 6 Log scale spectral irradiance of blue with and with spectral stray light correction.

A summary of the colorimetric analysis for these spectra is given in Table 2. The chromaticity shift in the CIE 1976 chromaticity coordinates caused by the spectral stray light over the full spectrum ranges from 0.0018 to 0.0040, depending on the color of the primary. These are significant color measurement errors that can be minimized by employing a spectral stray light correction on the spectroradiometer.

A similar analysis was also performed by isolating the spectral stray light contribution to within $\pm$50 nm of the primary peak. It is interesting to note that for this ideal case, the chromaticity difference only varies from 0.0002 to 0.0009. This suggests that it is difficult to determine the actual chromaticity when primary emission leakage occurs, even with spectral stray light correction, by adding up the ideal spectra of the primaries.

Table 2 Spectral stray light chromaticity difference

	CIE 1976 chromaticity difference (Δu'v')		
Primary	Red	Green	Blue
Full spectra	0.0040	0.0028	0.0018
Primaries only	0.0008	0.0009	0.0002

4. CONCLUSION

This study has highlighted some of the optical measurement challenges in evaluating retinal projection display performance. Commercial retinal projection displays may not exhibit additivity, and the emission spectra can have undesired leakage from other primaries. These complexities reinforce the value of spectral methods for improving the accuracy of device output power measurements. We also demonstrated the possible color measurement errors that could be avoided by using spectroradiometers with a spectral stray light correction. These methods can serve as valuable tools in the evaluation and development of laser-based projection systems.

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