DEVELOPMENT AND APPLICATION ISSUES OF A SPECTRALLY TUNABLE LED SOURCE

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ABSTRACT

A spectrally tunable solid-state source based on Light Emitting Diodes (LEDs) is being developed at the National Institute of Standards and Technology (NIST). The tunable source will emulate the spectral distributions of various light sources and can be utilized in calibrations of spectroradiometers, photometers, and colorimeters with reduced measurement uncertainty. Design issues of the tunable source, LED characterizations, source-distribution realizations, and colorimetric applications are discussed.

1. INTRODUCTION

As photometers and tristimulus colorimeters do not have the same (ideal) spectral responsivities as the CIE standardized color matching functions, the measurement uncertainty increases when the spectral distribution of a test source is different from the distribution of the standard source used for calibration. For example, the errors of a colorimeter that measures display colors can be large when it is calibrated against an incandescent standard lamp [1]. In order to reduce photometric and color measurement errors, we developed an experimental spectrally tunable source (STS) [2] [3]. The STS can be used as a transfer (but not a reference) source, having a spectral distribution approximately matched to that of the test source. In this case, the high accuracy of color measurement comes from detector (responsivity) standards [4]. The color calibration propagates from a reference photometer or colorimeter to a test photometer or colorimeter with a minimum increase in the measurement uncertainty if the test instrument is calibrated against the reference instrument [4-6] using the STS transfer source. Also, the STS can be used as a calibration source for spectroradiometers with reduced stray light errors in the ultraviolet and blue region, where traditional standard sources (e.g. tungsten lamps) do not have sufficient radiant power. High long-term stability is needed from the STS if it is to be usedas a reference standard source (to maintain the scale). A properly designed STS can calibrate accurately colorimeters and spectroradiometers in various applications. It can be used in both irradiance and radiance mode measurements. In irradiance mode, a photometer, colorimeter, or a spectrograph will measure the uniform irradiance from the STS at a certain distance. In radiance mode, a spectrally and spatially uniform exit port radiance is needed.

2. CONSTRUCTION OF THE SPECTRALLY TUNABLE SOURCE

The arrangement of the integrating sphere-based STS is shown in Figure 1. A large number of LEDs

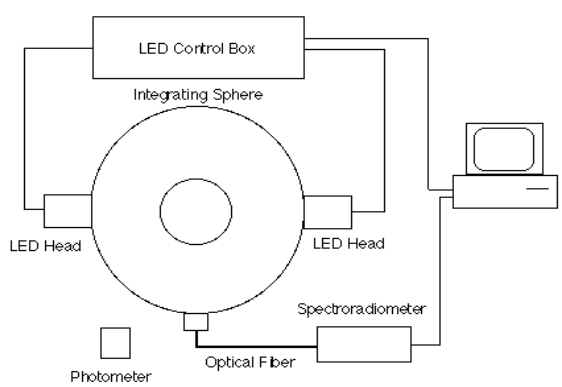

Fig. 1. Scheme of the spectrally tunable source setup.

with different spectral peaks and distributions are mounted in LED heads. The heads are attached to the sphere wall. The LEDs can be driven either individually or in different parallel/serial combinations with the stabilized output currents of a multi-channel LED control instrument. A diode array spectrometer and a photometer can be used as monitor devices to determine the real-time

radiometric/photometric output of the STS. A computer logs the output of the spectrometer and individually controls the drive current of the LEDs/LED groups to obtain the required (target) spectral distribution. As many of the LEDs are strongly temperature-dependent, thermal management is an important issue. The LED head design for the STS is shown in Fig. 2.

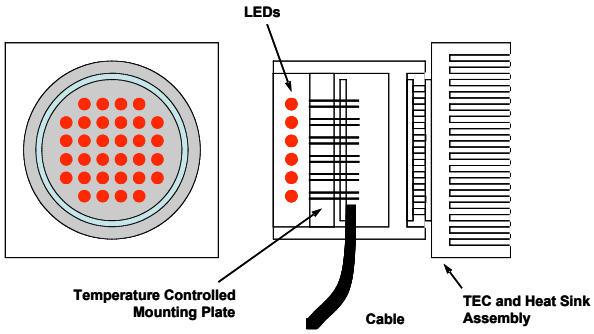

Fig. 2. Design of the LED head.

The figure shows how LEDs are mounted on a temperature-controlled mounting plate cooled by a thermoelectric cooler (TEC). A thermally conductive and electrically insulating filling material is applied inside of the head-cavity (among the LED leads and the cooled plate) to improve heat transfer and to perform uniform temperature distribution. The LED forward voltage is utilized as temperature monitor.

3. LED CHARACTERIZATIONS

As part of the TS development, a large number of LEDs were purchased. The LEDs were seasoned to minimize their time-dependent changes during applications. After seasoning, the LEDs were characterized. Luminance and chromaticity coordinates of red, blue, and green LEDs were measured versus drive-current [2]. The spectral power distributions and the radiometric stabilities were measured. All characterizations were made at a constant LED current of 20 mA. The spectral measurements were made with a well characterized spectroradiometer between 190 nm and 800 nm.

LED characteristics may vary depending on colors and manufacturers. The following results show both the variability depending on LED color and individual variations from the same batch. As an example, aging results of blue and red LEDs are shown in Figs 3 and 4. Figure 3 shows the 60 % to 70 % decrease of the luminous intensity of certain blue LEDs during a 325 hour burning time (at 25.5 °C). The large decrease is possibly dominated by the UV damage of the plastic cap and/or filling (glue) material. The less than 0.2 nm change of the peak wavelength (398 nm on the average) and the change of the dominant wavelength from 424 nm to 420 nm during the 325 hour burning time indicate a change in the asymmetry of the spectral power distribution (relative to the peak wavelength). As shown in Fig. 4, the relative luminous intensity degradation of some red LEDs was between 12 % and 15 % during a 140 hour burning time.

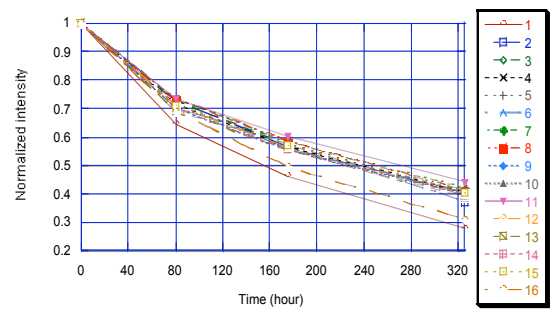

Fig. 3. Intensity change of blue LEDs.

The dominant wavelength decreased by less than 0.3 nm. These aging results show that a long seasoning time is needed for certain types of LEDs to obtain small enough intensity changes in following applications. For the above blue LEDs a seasoning time of more than 325 hours (possibly 500 hours) is needed to avoid significant intensity and dominant wavelength changes. The intensity changes were about three times smaller for the above tested red LEDs. The dominant wavelength changed about a factor of seven less for the red LEDs than for the blue LEDs.

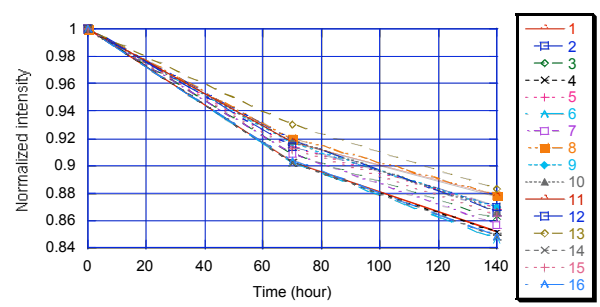

Fig. 4. Intensity changes of red (641 nm peak) LEDs.

Temperature dependent measurements were made on red, blue, yellow, and white LEDs at five different temperatures between 5 °C and 48 °C.

The average temperature coefficient of intensity, dominant wavelength, and forward voltage were determined for four LEDs from each type (color).

The smallest temperature coefficient of intensity of -0.04 %/°C to -0.07 %/°C was obtained for some model of white LEDs. The temperature coefficients were about twice as large for the blue LEDs (-0.07 %/°C to -0.16 %/°C). The intensity temperature coefficients were large, -1.0 %/°C for the red and -1.5 %/°C for the yellow LEDs. Figure 5 shows the temperature dependence of the relative luminous intensity for the yellow LEDs. A temperature coefficient for the dominant wavelength of 0.1 nm/°C was obtained for the yellow LEDs. While temperature stabilization is more important for the red and yellow LEDs, temperature control should be used for all LEDs.

For temperature sensing purposes, the temperature coefficients of the LED forward voltages were measured. The temperature coefficients were -1.3 mV/°C for the blue, -1.4 mV/°C for the red, -1.7 mV/°C for the yellow, and -2.4 mV/°C for the white LEDs.

4. REALIZATION OF TARGET SOURCE DISTRIBUTIONS

In spite of the measured LED changes the error of spectrum realizations depends only on the uncertainties of spectral measurements using the STS spectroradiometer. Stray light correction was applied to reduce spectral measurement errors.

Various target source-distributions for special and standard sources, such as discharge lamps, displays, solar or daylight distributions, etc. can be realized using a least square optimization method. Based on individual LED spectral measurements, a program calculates the sum of the differences in spectral distribution between the measured data and the target spectrum. The matching is achieved with a large number of iterations where the individual LED currents are increased or decreased in small steps. The integral-sum of the differences at each wavelength shows the degree of matching of the realized spectra.

The realized spectral distribution of the STS, in spite of the optimization, may not be matched well to the target distribution. The deviations can be caused by limitations in the availability of LEDs with the appropriate peak wavelengths or by their finite spectral widths (when matching very narrow-band peaks). The spectral distribution, once matched, can drift due to temperature differences, LED/material aging, and the non-linearity of the LED spectral power distribution versus feeding current. When these differences are small and slowly varying, a second optimization program can be applied that further reduces the difference between the target and measured (realized) source spectra. As an example, the realized spectrum (thick line) and the CIE D65 target spectrum (thin line) are shown in Fig. 6. The roughly 20 % deviations (right-Y axis) from the target function at 750 nm are caused by lack of available LEDs in that wavelength range.

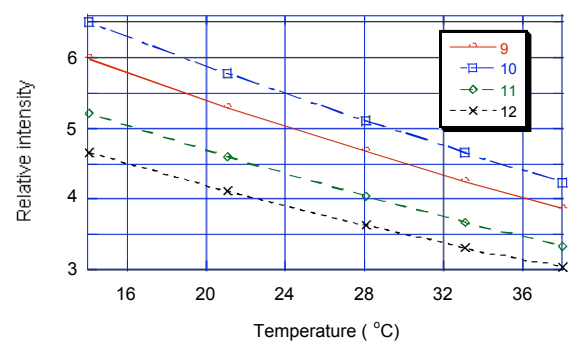

Fig. 5. Intensity versus temperature of yellow LEDs.

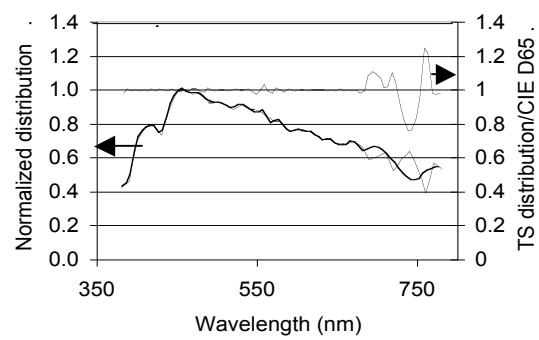

Fig. 6. Realized (thick curve) and CIE D65 (thin curve) distributions and their ratio.

5. USE OF STS AS A CALIBRATION SOURCE FOR COLORIMETERS

The STS, for example, can be used to calibrate a tristimulus colorimeter that measures many different type of displays. When the colorimeter is calibrated against a tungsten source (Illuminant A) as commonly done, the errors will vary depending on color and the type of display. For high accuracy

applications, the colorimeter needs to be calibrated against each types of real displays with known chromaticity coordinates. With STS, use of various real displays is not necessary.

As an example, the target distribution for a CRT display (white) and the realized (modeled) distribution (with the STS) are shown in Figure 7(a). In this simulation, 80 different color LEDs were used with 5 nm peak wavelength increments and a constant spectral width of 20 nm (FWHM). A simulation was performed to evaluate measurement errors of a colorimeter when measuring CRT colors (red, green, blue, and white). The colorimeter was calibrated first against CIE Illuminant A and then against the STS (matched to each CRT color). Figure 7(b) shows the Δx and Δy chromaticity coordinate errors (relative to the reference chromaticity coordinates) for the red, green, blue, and white colors of the CRT display. The color measurement errors decreased by about an order of magnitude, when the CRT display measuring tristimulus colorimeter was calibrated with the STS instead of the CIE Illuminant A.

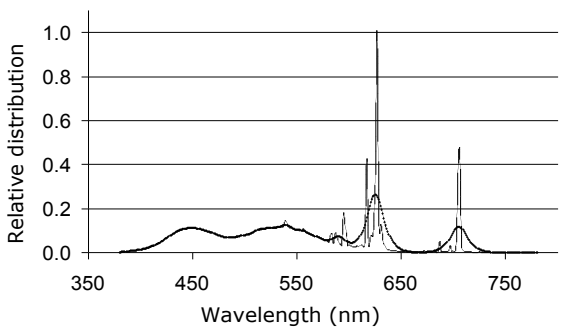

Fig. 7(a) Target (thin line and modeled (thick line) spectral distribution of a CRT display.

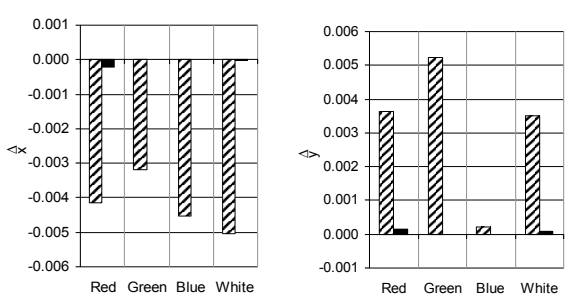

Fig. 7(b). Chromaticity coordinate measurement errors when the colorimeter is calibrated with the STS (black bars) and CIE Illuminant A (hatched bars)

The realized spectral match with the STS will be poorer if less number of LEDs are used (e.g., with 10 nm or 20 nm peak wavelength intervals). The required quality of matching can be evaluated from the calculations of the Δx and Δy as presented in Fig. 7(b). Our further simulation analyses predict that STS of 20 nm LED intervals still works well for most cases, and the matching of spectra need not be precise. The mismatch of the realized distribution primarily depends on the shape of the spectral structures (narrow peaks). The required quality, i.e., the allowable spectral mismatch to the target source distribution can be determined from these calculations.

The STS can be relatively simple and inexpensive when it realizes the target source distribution with the allowable spectral mismatch determined above. A tristimulus reference colorimeter [5] can be calibrated against a reference detector of known spectral responsivity [6] using the realized source distribution of the STS. With the STS, the reference color scale can be propagated to field-level tristimulus colorimeters with a minimum increase in the color measurement uncertainty. The advantage of this detector-based color calibration method is that only a short-term stability is needed for the STS.

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