Spectral matching with an LED-based spectrally tunable light source

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ABSTRACT

A spectrally tunable light source using an integrating sphere with a large number of LEDs has been designed and constructed at the National Institute of Standards and Technology (NIST). The source is designed to have a capability of producing any visible spectral distribution, mimicking various light sources in the visible region by feedback control of the radiant power emitted by individual LEDs. The spectral irradiance or radiance of the source is measured by a standard reference instrument; the source will be used as a transfer standard for colorimetric, photometric and radiometric applications. A series of simulations have been conducted to predict the performance of the designed tunable source and source distributions have been realized for a number of target distributions.

Keywords light emitting diode, LED, lighting, tunable source, radiometry, spectrometry

1. INTRODUCTION

Light emitting diode (LED) applications have recently grown significantly, in particular since the development of high intensity blue and white light LEDs. LED-based, "solid-state" lighting is available in a surprising number of end-use products, for example as exit signs, traffic lights, decorative lighting, nightlights and neon-replacement, display lighting, automobile and aircraft lighting. Currently, a wide variety of LEDs are available with peak wavelengths covering the visible and adjacent spectral regions.

Spectral matching of light sources is often required, e.g., to simulate daylight illuminants for colorimetric measurements or visual inspection. Utilizing LEDs with different spectral power distributions, and controlling the radiometric output of each type of LED, it is possible to make a spectrally tunable light source (STS) that is able to provide a high fidelity spectral match to a specific "target" spectral power distribution (SPD). Such LED sources were reported in the past but some are for producing given colors (chromaticity) [1] and others attempted to match the spectrum to a given SPD [2] but desirable level of spectral control has not been achieved.

An STS using an integrating sphere and a large number of LEDs has been developed at NIST. The design of the source and a simulation of expected spectral matching were previously reported [3]. In this paper, we describe the construction and the performance of the STS developed, which is able to approximate the distributions of a wide variety of light sources, including daylight illuminants, with high fidelity. The STS' output matching the SPDs of several different light sources are presented and additional applications of the source are discussed.

When the STS is calibrated for absolute spectral irradiance or radiance, it can be used as a transfer source for spectroradiometers as well as for colorimeters and photometers. In addition to conventional standard source spectra, the STS can simulate SPDs of special sources such as display red, green, blue and white; traffic signals; and discharge lamps. Also, a tunable source can approximate novel and unique spectral distributions that cannot be realized using conventional sources.

Consider photometric applications for example. Many photometry calibration facilities are equipped with large number of different standard sources of optical radiation, e.g. different types of lamps. Control and maintenance of these sources are very inconvenient and expensive. A STS that can mimic different source spectral distributions, *e.g.* the spectral distributions of different standard optical sources, would eliminate the need for maintaining a wide variety of different standard sources.

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2. DESIGN OF A TUNABLE LED-BASED SOURCE

The STS is an integrating sphere source illuminated by a large number of LEDs having different spectral peaks and distributions; a schematic diagram of the source is shown in Fig. 1. The LEDs can be driven and controlled individually with a 256-channel, computer-controlled power supply. The large number of spectral channels helps facilitate accurate matching of fine structure in target source SPDs. A diode array spectroradiometer and a photometer are used as monitor devices to determine the real-time radiometric and photometric output of the STS, respectively. A computer logs the output of the spectroradiometer and individually controls the drive currents of the LEDs to obtain the required target source SPD. The LEDs are mounted in 10 LED heads (maximum 32 LEDs in each head) equipped with a temperature-controlled mounting plate to cool the LEDs and stabilize their temperature.

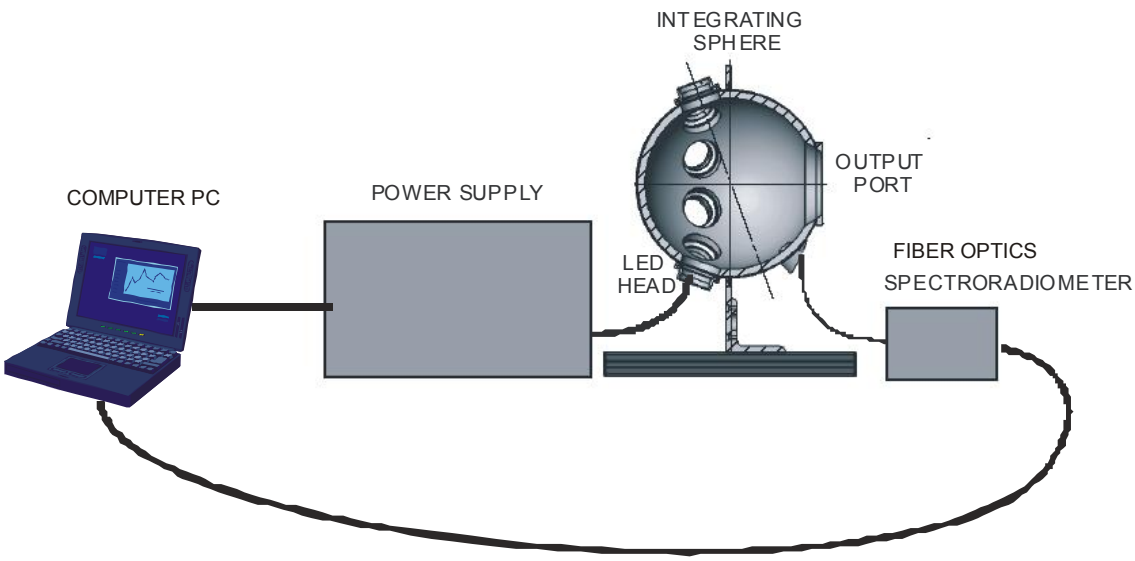

Fig. 1. Configuration of the NIST STS.

3. SIMULATION OF THE STS

To give us guidelines on the number of LEDs necessary to match a variety of target source SPDs, simulations were conducted to evaluate the accuracies of spectral matches using modeled [4] LED SPDs. The modeled LED distributions were based on normalized Gaussian functions with spectral widths (FWHM) of 20 nm. Simulations were run with 5 nm, 10 nm and 20 nm LED peak wavelength intervals over the range from 380 nm to 780 nm. Thus, a total of 80, 40 or 20 LEDs were used in the simulations, corresponding to intervals between LED peak distributions of 5 nm, 10 nm or 20 nm, respectively. An optimization algorithm was developed to simulate the relative power to each LED to generate a simulated spectral match to any input target spectrum. In the optimization, the values of power coefficients k_i , $i = 1...n$ for the n different LEDs are determined. The power coefficient k is strongly related to the current applied to, or radiant flux from, the LED belonging to that variable. The resulting spectrum is the sum of all modeled LED SPDs weighted by the k 's calculated according to the optimization algorithm.

The optimization consists of the following steps:

1) Selection of the initial values of power coefficients $k_i^{(0)}$, $i = 1...n$ of i-th LED; they can be any positive number.

2) Calculation of the j-th value of k_i from the *(j-1)*-th value, based on the partial derivative with respect to k_i of the square of the difference between the target spectrum and the STS spectrum built up from the LED spectra weighted by the variables k:

$$k_i^{(j)} = k_i^{(j-1)} - a \frac{\partial \sum_{380}^{780} \left(\sum_{i=1}^{n} k_i^{(j-1)} S_{\mathrm{LED}_i}(\lambda) - S_{\mathrm{TARGET}}(\lambda) \right)^2}{\partial k_i^{(j-1)}}, \tag{1}$$

where a should be between 0 and 1. To achieve an optimal calculation time while still ensuring convergence of the solution, a was set to 0.001.

3) Continuation of the iterations until the solution converges, that is until

$$\sum_{380}^{780} \left| \sum_{i=1}^{n} k_i^{(j)} S_{\mathrm{LED}_i}(\lambda) - S_{\mathrm{TARGET}}(\lambda) \right| = \sum_{380}^{780} \left| \sum_{i=1}^{n} k_i^{(j-1)} S_{\mathrm{LED}_i}(\lambda) - S_{\mathrm{TARGET}}(\lambda) \right|. \tag{2}$$

The equality is obtained from a large number of iterations where the individual LED currents (power coefficients k) are increased or decreased in small increments. It can be interpreted that the algorithm stops when the values k_i reach a steady-state solution. The individual LED currents are obtained from the optimization. The integral-sum of the differences at each wavelength is an indication of the quality of the realized spectral match.

It is difficult to make general, qualitative statements about the quality of the spectral match. One of the simple methods, which can enable describing the quality of the spectral match, can be based on the parameter p, which is the ratio of the integrated absolute difference between test and target source distributions to the integrated target source distribution:

$$p = \frac{\sum_{380}^{780} \left| \sum_{i=1}^{n} k_i^{(j-1)} S_{\mathrm{LED}_i}(\lambda) - S_{\mathrm{TARGET}}(\lambda) \right|}{\sum_{380}^{780} S_{\mathrm{TARGET}}(\lambda)}. \tag{3}$$

The parameter p gives a rough estimation of the quality of the spectral match of the STS to a target source distribution.

Figures 2 to 13 show four different target SPDs and their approximations obtained from simulations using sets of 20, 40 and 80 LEDs, respectively. To test the quality of the optimization algorithm, four different target light sources were chosen. To test the simulated source match to a broad target spectrum, the CIE standard daylight illuminant D65 and the SPD of a High Intensity Discharge (HID) lamp were taken under consideration. Two fluorescent lamp (FL) spectra were chosen as examples of sources having narrow peaks together with broad spectral features. Figures 2 to 4 correspond to derivations of the CIE standard daylight illuminant D65. As can be seen in the figures, the set of 20 LEDs is not able to match the target distribution with high spectral fidelity, and parameter p is equal to 0.079. For the sets of 40 and 80 LEDs, the simulated STS SPDs agree much better with the D65 SPD, and provide better matches over finite spectral segments. The parameter p is equal to 0.004 and 0.003 for the simulated STS using sets of 40 and 80 LEDs, respectively.

Figures 5 to 7 show similar results for a HID lamp. Again, the set of 20 LEDs is not able to ideally reproduce the target lamp's SPD, while the set of 40 LEDs is able to reproduce the target SPD with high spectral fidelity. The parameter p for set of 20 LEDs is equal to 0.074, and for 40 and 80 LEDs value of parameter p is 0.008 and 0.007.

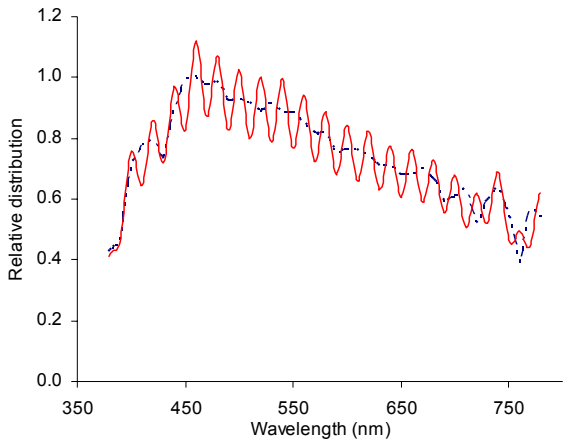

Fig. 2. SPD of daylight illuminant D65 (dashed line) and the STS model distribution with 20 nm LED intervals (solid line).

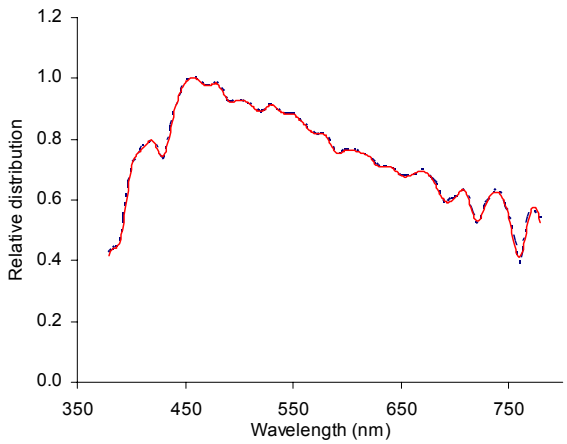

Fig. 3. SPD of daylight illuminant D65 (dashed line) and the STS model distribution with 10 nm LED intervals (solid line).

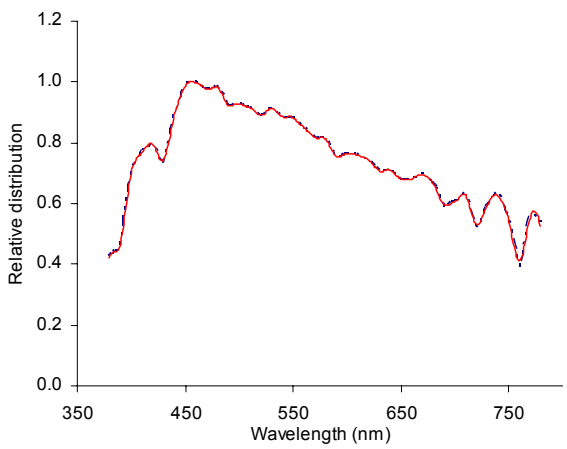

Fig. 4. SPD of daylight illuminant D65 (dashed line) and the STS model distribution with 5 nm LED intervals (solid line).

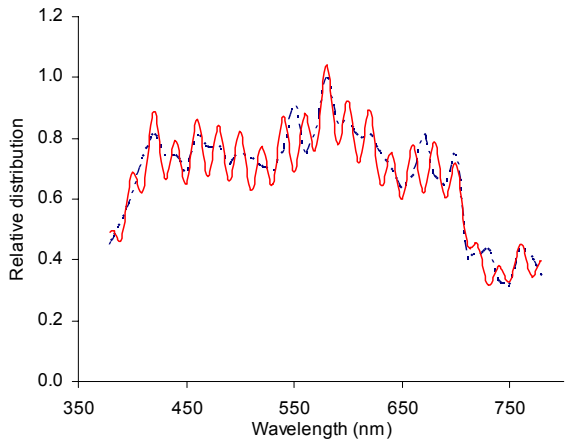

Fig. 5. SPD of a HMI HID lamp (dashed line) and the STS model distribution with 20 nm LED intervals (solid line).

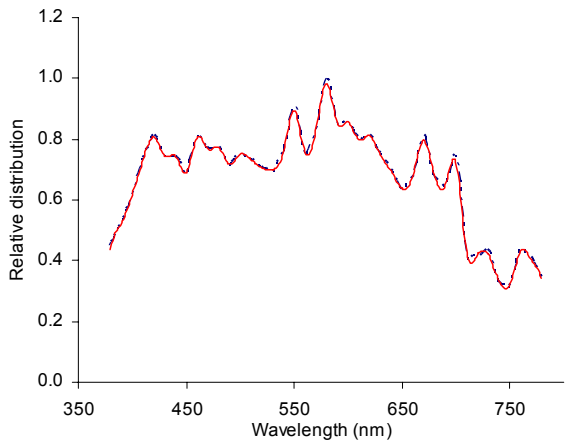

Fig. 6. SPD of a HMI HID lamp (dashed line) and the STS model distribution with 10 nm LED intervals (solid line).

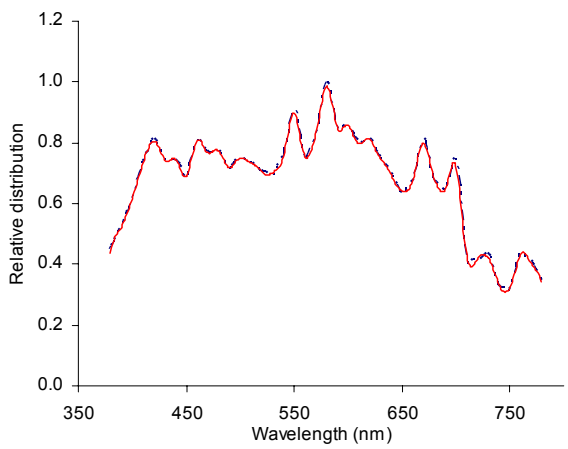

Fig. 7. SPD of a HMI HID lamp (dashed line) and the STS model distribution with 5 nm LED intervals (solid line).

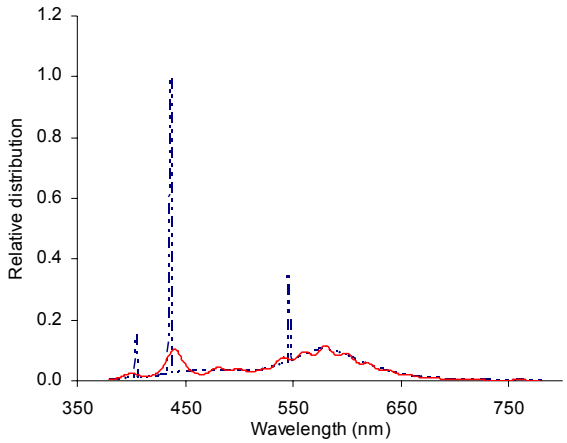

Fig. 8. SPD of a cool white FL (dashed line) and the STS model distribution with 20 nm LED intervals (solid line).

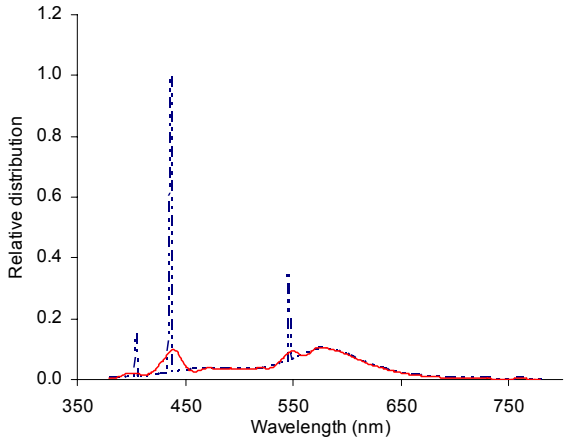

Fig. 9. SPD of a cool white FL (dashed line) and the STS model distribution with 10 nm LED intervals (solid line).

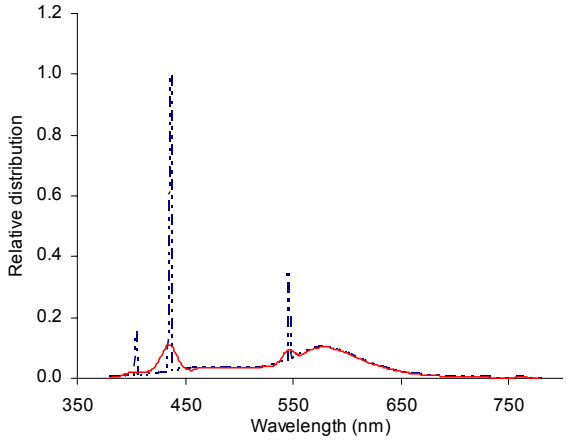

Fig. 10. SPD of a cool white FL (dashed line) and the STS model distribution with 5 nm LED intervals (solid line).

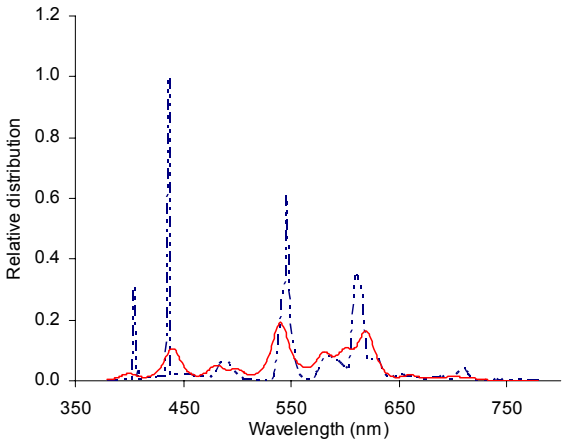

Fig. 11. SPD of a tri-phosphor FL lamp (dashed line) and the STS model distribution with 20 nm LED intervals (solid line).

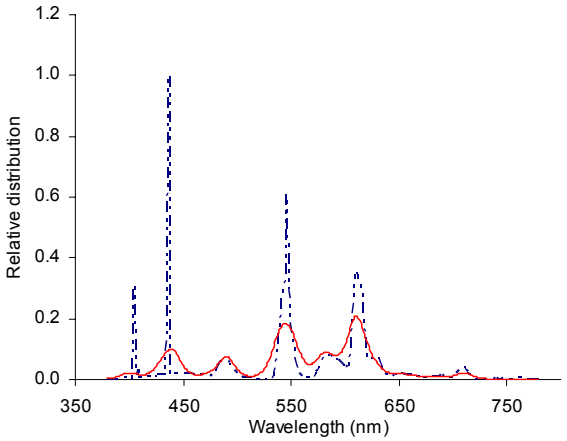

Fig. 12. SPD of a tri-phosphor FL lamp (dashed line) and the STS model distribution with 10 nm LED intervals (solid line).

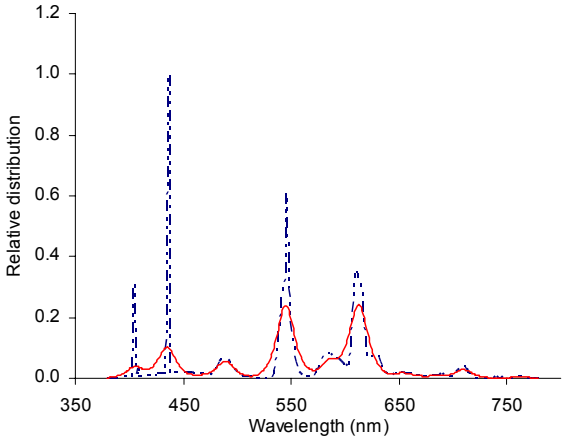

Fig. 13. SPD of a tri-phosphor FL lamp (dashed line) and its STS model with 5 nm LED intervals (solid line).

Figures 8 to 10 correspond to a cool white FL lamp and Figures 11 to 13 correspond to a tri-phosphor FL lamp. As can be seen, the target SPDs have narrow peaks with half-widths less than 5 nm superimposed onto a broad underlying spectrum. Such narrow features cannot be matched by LEDs having 20 nm widths. The set of 20 LEDs does not match the peaks in the target distribution well, and the simulated STS distribution has oscillations in the broad spectral regions. The parameter p for the STS using a set of 20 LEDs matching cool white FL lamp is equal 0.29, and for tri-phosphor FL lamp is 0.77. The best agreement between target and STS calculated output was achieved for the set of 80 LEDs. However, the difference in the quality of the SPD match for sets of 80 and 40 LEDs, as measured by the parameter p, was not significant: for the cool white FL lamp, p changes from 0.25 to 0.24, and for the tri-phosphor FL lamp, p changes from 0.68 to 0.59.

4. CONSTRUCTION OF THE STS

4.1. LED selection and characterizations

Prior to the final design of the STS LED heads, a large number of different types of LEDs were obtained and evaluated for total radiant flux, spectral power distribution, and peak wavelength. The LEDs were seasoned prior to incorporation into the source to improve their radiometric stability. After seasoning, the LEDs were characterized. The spectral power distributions were measured versus drive-current. Spectral measurements were made with a spectroradiometer between 190 nm and 800 nm. LED characteristics vary significantly depending on material composition and manufacturer. Figure 14 shows the values of radiant flux [mW] for 160 different LEDs versus their peak wavelength. The measurements were made against standard LEDs using a 0.5 m integrating sphere with relative expanded uncertainties (k=2) of less than 10 %. As shown in Fig. 14, the level of the radiant flux depends largely on the LED color (peak wavelength). The yellow-green LEDs are dim compared to blue, blue-green and red LEDs. Additionally, it is difficult to find LEDs between 525 nm and 555 nm (the so-called "green hole"). A limited number of LEDs are available between 720 nm and 760 nm.

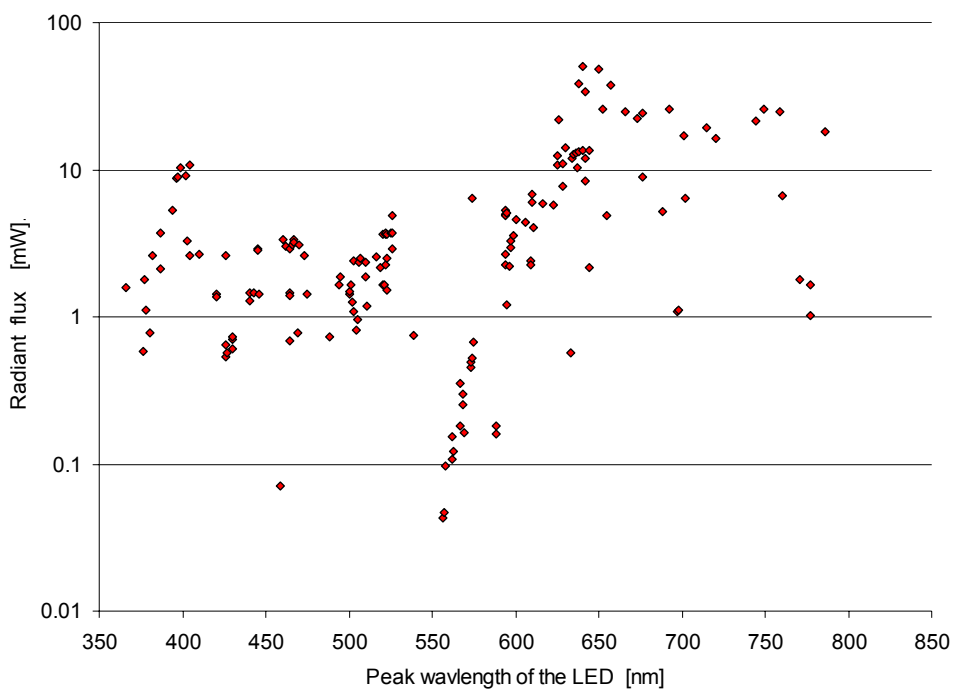

Fig. 14. Total radiant flux of the LED samples to be used in the STS plotted as a function of their peak wavelengths.

Figure 15 shows the SPDs of the set of 35 LEDs chosen to use in the first version of STS. Many LEDs have spectral widths larger than 20 nm (FWHM). Large spectral widths can create problems with matching target sources having narrow spectral features (Fig. 19 and Fig. 20). Additionally, lack of LED in spectral range from 530 nm to 590 nm can cause a problem with matching even relatively broad peaks in this spectral range (Fig. 17 and Fig. 18).

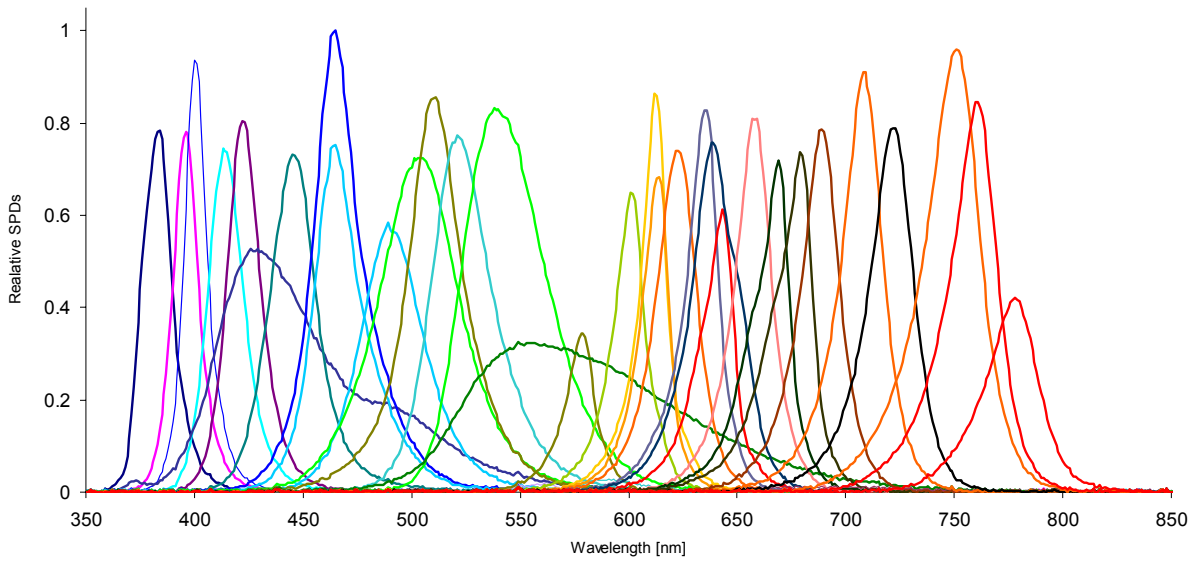

Fig. 15. Spectral power distributions of the set of 35 LEDs chosen to use in the STS.

4.2. Instrumentation of the system

The SPS developed at NIST is shown at Fig. 16. The STS integrating sphere (30 cm diameter) has an opening of 10 cm maximum diameter is illuminated by a 35 LED channel. Each LED is driven and controlled individually with, computer-controlled power supply. The special developed software allows us to control each channel individually.

Fig. 16. The STS developed at NIST.

5. REALIZED STS SPECTRAL DISTRIBUTIONS

The STS is designed to match any spectral distribution over the range from 380 nm to 780 nm. The matching of the SPDs is realized using the optimization algorithm described in Section 3, based on measurements by a reference spectroradiometer. The optimization takes a long time due to a large number of iterations between measurements and calculations. Once the optimized condition is achieved, the drive currents of all the LEDs are recorded, and the same SPD can be reproduced by using the same sets of drive currents. The realized spectral distribution of the STS (Figs. 17 to 20) can be different from the target distribution due to limitations in the optimization algorithm as well as limitations in the availability of LEDs with the appropriate peak wavelengths, their finite spectral widths (SPD curves), and drifts in their radiometric output due to temperature fluctuations, aging, etc. When the drifts are small and slowly varying, a second optimization program (running in real time) can be used to maintain the constant SPD of the source. The luminance of the STS, depends on the specific spectral distribution desired, is typically between several hundred to one thousand cd/m^2 for white light spectra.

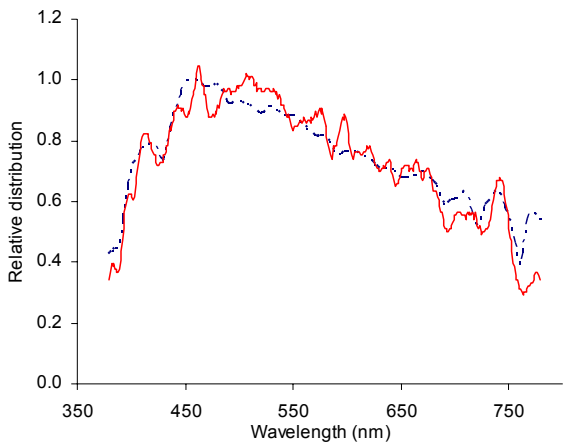

Fig. 17. SPD of CIE illuminant D65 (dashed line) and the STS output measured by spectroradiometer (solid line).

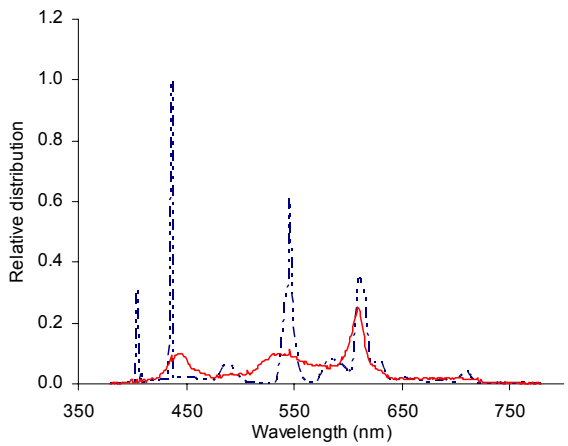

Fig. 19. SPD of a tri-phosphor FL (dashed line) and the STS output measured by spectroradiometer (solid line).

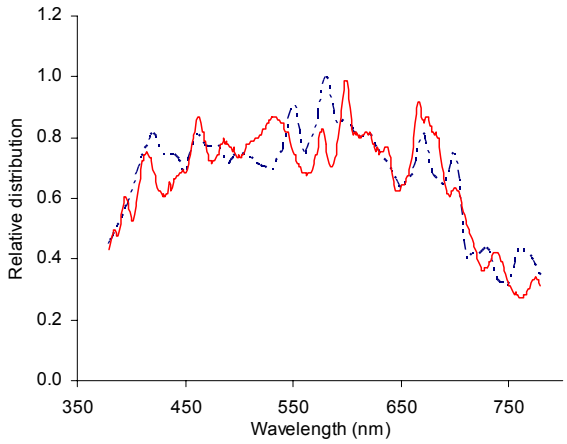

Fig. 18. SPD of a HID – HMI (dashed line) and the STS output measured by spectroradiometer (solid line).

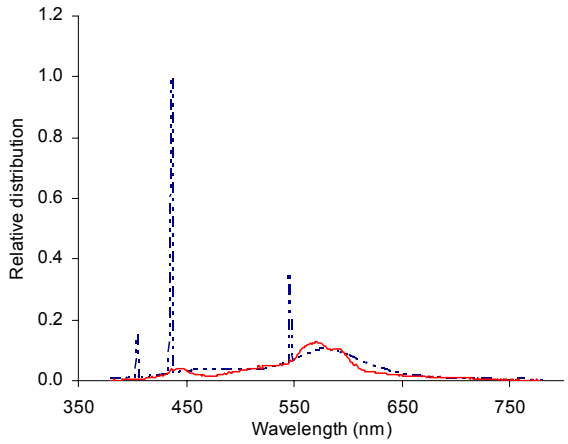

Fig. 20. SPD of a cool white FL (dashed line) and the STS output measured by spectroradiometer (solid line).

The parameter p for D65 realization was 0.068. This value is close to the value of p calculated for the STS spectrum based on the simulated 20 LED STS source: 0.076. For the other example source distributions realized by the STS, parameter p is comparable to, but slightly larger than, p calculated for the simulated 20 LEDs STS. The parameter p was 0.10 when simulating the HID lamp distribution, 0.34 for the cool white FL lamp distribution and 0.84 for the tri-phosphor FL lamp distribution, respectively.

6. CONCLUSIONS

A spectrally tunable LED source (STS) has been designed and developed at NIST. A series of simulations have been conducted to clarify design requirements and predict the performance of the designed tunable source. Based on this information the real STS was designed and constructed. The source can approximate various CIE daylight illuminants (D65, etc.) and common lamp spectral distributions for other photometric and colorimetric applications, and may be useful for visual experiments on colorimetry.

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