Letter

Design and Development of an LED-Artificial Sunlight Source System Prototype Capable of Controlling Relative Spectral Power Distribution

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ABSTRACT

An artificial sunlight source system that is able to produce a spectral power distribution (SPD) approximating ground level sunlight (GLS) as well as arbitrarily modified SPDs would facilitate the investigation of living-organism responses in various light environments. A prototype of a light emitting diode (LED)-artificial sunlight source system was designed as a first step towards the development of such a system. The LED-artificial sunlight source system produces a relative SPD (composition of wavelengths) approximating GLS in a wavelength range of 400-900 nm by applying different voltages to LEDs with 32 different peak wavelengths (395 to 910 nm). The irradiance of the system is as low as less than one-tenth of GLS. In addition, the system can produce time-varying light in any order at time intervals greater than one second by preparing a series of sets of applying different voltages to LEDs. The configuration of the LED-artificial sunlight source system, the method used to produce the desired relative SPDs, and testing of the system are described herein. We also discuss necessary improvements to achieve an artificial sunlight source system that can produce an SPD approximating GLS.

KEYWORDS: artificial light, LED, spectral irradiance, spectral power distribution, sunlight

1. Introduction

Living-organism responses to different static monochromatic light sources have been extensively investigated[1)2)]. However, it should be more interesting to investigate living-organism responses to dynamic and combined light effects. An artificial sunlight source system that is able to produce arbitrarily modified spectral power distributions (SPDs) [W nm^{-1}] from an SPD that approximates ground level sunlight (GLS) would facilitate the investigation of living-organism responses in various light environments. There is a wide variety of applications of such a system, not only in plant sciences but also in animal and human sciences. There have been several reports on plant responses to monochromatic light from light emitting diodes (LEDs) or addition of monochromatic light to wide spectrum light[3)-5)]. The responses of cultured animal cells[6)7)] and transplant seedlings[8)] to laser light with a full width at half maximum of 1 nm have also been reported. However, to the best of our knowledge, there have been no reports on an artificial sunlight source system as described above.

Such an artificial sunlight source system requires luminescent devices, such as LEDs or lasers, that each produces a different monochromatic light with a narrow wavelength. LEDs were selected for the artificial sunlight source system because they have a wide variety of peak wavelengths, are easy to control their radiant flux while discharge lamps are difficult to control, are able to constitute a compact light source enough for practical use with multiple LEDs each with a different peak wavelength since their dimension is considerably small, and are easy to handle. Using LEDs with such features, we designed and developed a prototype artificial sunlight source system that is able to produce a 'relative' SPD (*i.e.* composition of wavelengths) that approximates GLS in a wavelength range of 400-900 nm. This represents the first step toward the development of an artificial sunlight source system capable of both producing an SPD that approximates GLS at any place on the earth and statically and dynamically producing arbitrarily modified SPDs. In this paper we describe the configuration of the LED-artificial sunlight source system, the method used to produce the desired relative SPDs, and testing of the current system. We also discuss improvements that are necessary to achieve an artificial sunlight source system that can produce an SPD approximating GLS.

2. Hardware and software configurations of the LED-artificial sunlight source system

2.1 Light source unit and spectral power distribution (SPD) control system

The LED-artificial sunlight source system (Fig. 1) is composed of a light source unit (composed of a LED module and a hollow conical reflection condenser; Fig. 2) and an SPD control system. The LED module (160 x 160 mm) is a 2 x 2 square of four sub-modules (Fig. 3), each composed of 256 LEDs, which have 32 different peak wavelengths (395 to 910 nm), and are arrayed on a glass-epoxy universal circuit board (ICB500G, Sunhayato Corp., Tokyo). The 256 LEDs are arrayed in a square formation of 16 x 16 LEDs, which occupies 80 x 80 mm on the universal circuit board. 256 LEDs were installed as a result of calculating the proportion of each type of LED required (as described below). The LEDs were clear epoxy resin-mold type with an outer dimension of 3.0 or 3.1 mmϕ (see Table 1 for model codes, manufacturers, and fundamental specifications).

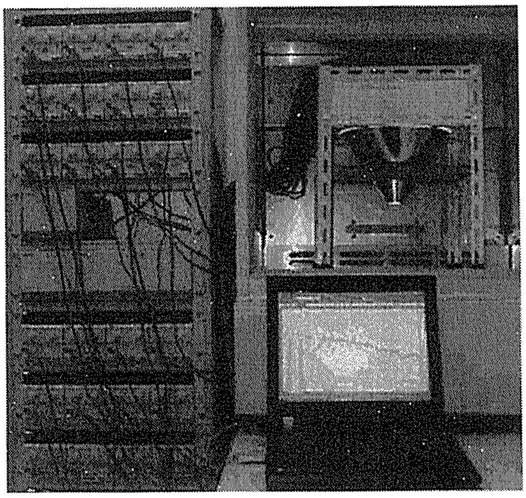


Figure 1 The LED-artificial sunlight source system.
Left: 32 DC power supplies, the DC power supply controller, and 3 controller expansion units mounted in a rack; right upper: the light source unit (composed of a LED module and a hollow conical reflection condenser) supported by an iron frame in a temperature-controlled chamber; right lower: a laptop computer

A hollow conical reflection condenser plated with silver on both sides condenses and mixes the light from the LED array. The base (250 mmϕ) of the condenser is placed onto the LED array and the tip of the condenser is trimmed away to create a light outlet (30 mmϕ). The height of the condenser from base to trimmed edge is 165 mm. The light source unit is placed in a 20°C temperature-controlled chamber to stabilize the SPD when the LEDs are turned on.

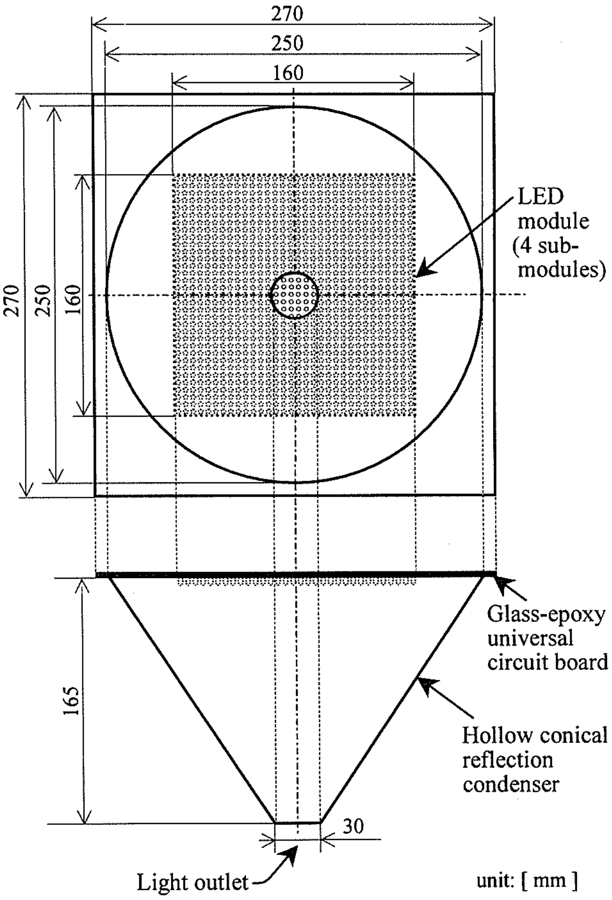


Figure 2 A Schematic diagram of the light source unit (composed of a LED module and a hollow conical reflection condenser). The small circles in dotted and solid lines in the upper diagram denote LEDs installed on the circuit board

The SPD control system is composed of 32 direct current (DC) power supplies (PMC35-1A, PMC70-1A, Kikusui Electronics Crop., Yokohama, Japan), a DC power supply controller (PIA4810, Kikusui Electronics Crop.), 3 controller expansion units (PIA4820, Kikusui Electronics Crop.) that were connected to the DC power supply controller, and a laptop computer used to send voltage value signals to the DC power supply controller. The DC power supply controller and controller expansion units are equipped with 4 control boards (OP02-PIA, Kikusui Electronics Crop.), each capable of analog control of 2 DC channels. In sum, the SPD control system is capable of controlling the 32 DC power supplies, each of which controls one of the 32 different peak wavelength LED types. The system thus controls the SPD [W nm^{-1}] of radiated light from the light source unit.

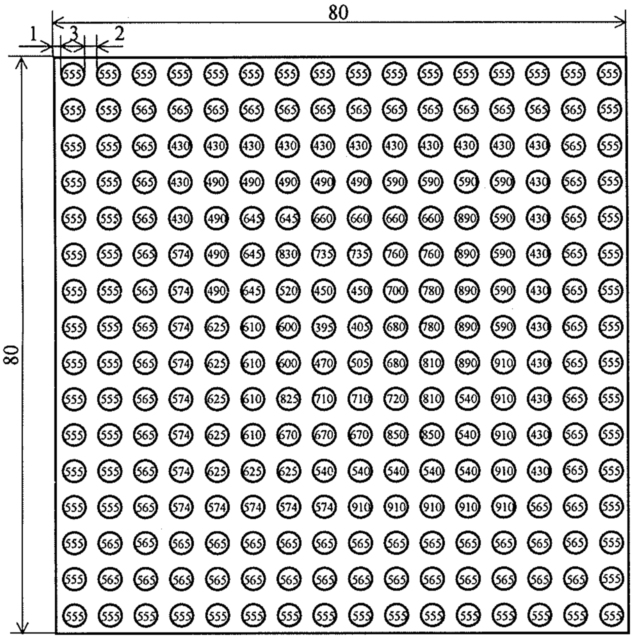


Figure 3 A Schematic diagram of the LED sub-module. The circles denote LEDs installed on a circuit board and the numbers in the circles indicate the typical peak wavelengths of the LEDs

It is easier to measure spectral irradiance (SI) [W m^{-2} nm^{-1}] at the light outlet with a spectroradiometer than to measure SPD produced from the LED module, which requires special instrumentation. Therefore, we have chosen to control the SPD of radiated light by controlling SI at the light outlet of the conical reflection condenser.

2.2 Determining the proportion of each type of LED

We determined the proportion of LEDs of each wavelength to install using the spectral radiant flux (SRF) [W nm^{-1}] from each type of LED so that the light source unit can produce a relative SPD approximating that of sunlight within the range of 400-900 nm. For this purpose, the SRF of each type of LED was measured at a forward current of 10 mA (less than one-third of the maximum rated forward current for all LEDs) using an integrating sphere we designed using a diffused reflection board (MCPET®, Furukawa Electric Co., Ltd., Tokyo). Second, the SI of sunlight was recorded at noon on a clear day in May in Tokyo. The measurement was taken with a spectroradiometer (MS-720, EKO Instruments Co. Ltd., Tokyo) and was smoothed using the moving average (±15 nm) method in order to use the shape of the SI curve as the reference relative SPD curve of sunlight (Fig. 4). Finally, the installation proportion of each type of LED was determined using the SRF data for each wavelength LED such that the SRF curve from one LED sub-module roughly approximates the reference relative SPD curve of sunlight. The results showed that each LED sub-module should comprise 1-72 LEDs of each type and 256 LEDs in total (Table 1). The LEDs were arrayed spirally in a square formation so that the LEDs installed in smaller number occupied areas around the center of the LED sub-module (Fig. 3). As described above, four LED sub-modules were placed 2 x 2 to create the LED module (Fig. 2).

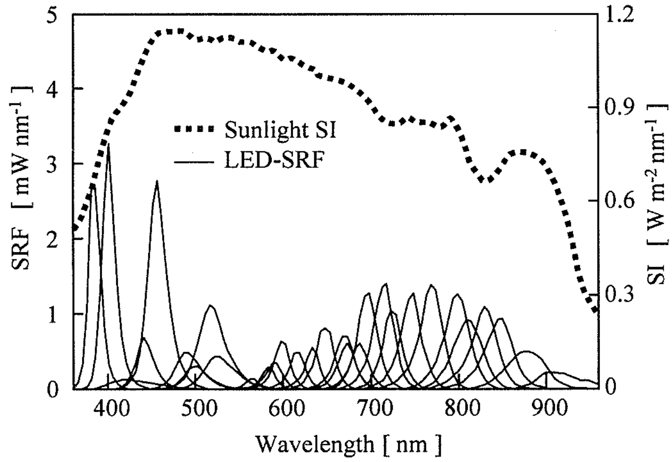


Figure 4 The spectral radiant flux (SRF) of each type of LED measured at a forward current of 10 mA (LED-SRF) and the spectral irradiance (SI) of sunlight recorded at noon on a clear day in May in Tokyo (Sunlight SI). The SI of sunlight was smoothed using the moving average (±15 nm) method

3. Processes for producing a desired SPD or SI at the light outlet

This artificial sunlight source system does not produce an SPD approximating GLS but rather a 'relative' SPD approximating GLS as well as modified SPDs from the approximate 'relative' SPD. Although the magnitudes of these SPDs are rather different, there is no difference in the process used to produce them. Desired SPDs or SI at the light outlet can be produced by sending a set of appropriate voltage signals, determined beforehand, to the DC power supply controller to be applied to each type of LED in the light source unit. To determine a set of appropriate voltages, we decided to prepare a database of SI at the light outlet against applied voltage (voltage-SI database) for the arrayed LED(s) with each peak wavelength. The following steps were required to prepare the voltage-SI database.

Although LEDs are generally controlled by varying the current, it was possible that excessive current supply caused by a sudden variation in load would damage the LEDs. To avoid this, we used voltage control: there was no possibility that the maximum output-voltage variation (3 mV, specified in the catalog) for the power supply would cause severe damage to any LEDs.

Table 1 Typical peak wavelengths of LEDs (TPW), model codes, manufacturers, standard rated forward voltages (SRFV), maximum rated forward currents (MRFC), viewing half angles (VHA), and LED numbers installed for the LED module of the artificial sunlight source system

TPW [nm]	Model code	Manu-facturer	SRFV [V]	MRFC [mA]	VHA [°]	LED No.
395	L395-36V	EPTX[z)]	3.8	30	28	4
405	L405-36V	EPTX	3.8	30	28	4
430	L430-36U	EPTX	3.8	30	30	88
450	L450-36U	EPTX	3.6	30	30	8
470	NSPB320BS	NCH[y)]	3.6	30	22	4
490	L490-36U	EPTX	3.5	30	32	32
505	L505-36U	EPTX	3.5	30	28	4
520	E1L31-AG0A	TYD[x)]	3.3	30	20	4
540	NSPG320BS	NCH	3.5	30	22	28
555	L555-36	EPTX	2.2	30	30	288
565	L565-36U	EPTX	2.2	30	30	256
574	TLGE125	TSHB[w)]	2.27	50	18	48
590	L590-36V	EPTX	2.0	50	40	32
600	L600-36V	EPTX	2.0	50	40	8
610	L610-36V	EPTX	2.0	50	40	16
625	L625-36V	EPTX	2.0	50	40	28
645	L645-36V	EPTX	2.2	50	40	16
660	L660-36U	EPTX	1.9	50	30	16
670	L670-36V	EPTX	1.8	50	30	12
680	L680-36AU	EPTX	1.9	50	30	8
700	L700-36AU	EPTX	1.9	50	30	4
710	L710- 36AU	EPTX	1.9	50	30	8
720	L720-36AU	EPTX	1.9	50	30	4
735	L735-36AU	EPTX	1.85	75	30	8
760	L760-36AU	EPTX	1.85	100	30	8
780	L780-36AU	EPTX	1.85	100	30	8
810	L810-36AU	EPTX	1.6	100	30	8
825	L825-36AU	EPTX	1.6	100	30	4
830	L830-36AU	EPTX	1.6	100	30	4
850	LN850-36U	EPTXE	1.5	100	30	8
890	L890-36AU	EPTX	1.45	100	30	20
910	L910-36	EPTX	1.4	100	30	36

z) Epitex Incorporation, Kyoto, Japan

y) Nichia Corporation, Tokyo, Japan

x) Toyoda Gosei Co., Ltd., Aichi, Japan

w) Toshiba Corporation, Semiconductor Company, Tokyo, Japan

First, SI at the light outlet was measured when each type of LED was turned on at the minimum voltage to emit light, at the standard rated forward voltage, and at five equal intervals between these values. The minimum voltage to emit light for each type of LED was determined as the voltage at which an obvious spectrum with its expected peak was observed by spectroradiometer measurement. SI at the light outlet was measured under no light leak conditions by tightly fitting the light outlet to the sensor window of the spectroradiometer.

Second, 51 SIs, which correspond to 51 voltage levels to be applied, were obtained for each type of LED by linear interpolation of adjacent pairs of measured SI into 10 segments. In this manner, a voltage-SI database of 51 (voltage levels) x 32 (peak wavelengths) SI data set was constructed. Using this database, it was possible to estimate SI at any combination of applied voltages to different LED types. Thus, if a target SI is provided, it is possible to determine a combination of applied voltages that will produce the best-approximated SI to the target SI.

A best-approximated SI to a target SI is determined by the following steps after the target SI is provided to a computer program:

(1) integrated squares of difference are calculated every 1 nm from 400 to 900 nm between the target SI and approximated SI for each of the following three cases: maintaining the applied voltage (0 mV at first) to the 395 nm LED type, increasing the applied voltage by one level, and decreasing the applied voltage (when the voltage is greater than 0 mV) by one level of the 51 voltage levels in the voltage-SI database;

(2) the case that provides the minimum value of integrated squares of difference is selected;

(3) steps 1 and 2 are conducted for each type of LED in ascending order of peak wavelength, and the set of selected voltages and integrated SI to be produced by the set of selected voltages are stored every time the voltage selection has been performed for each type of LED;

(4) when step 2 is completed for the 910 nm LED type, *i.e.* the end of one cycle of each LED type, the set of selected voltages and the integrated squares of difference are stored;

(5) when the integrated squares of difference at the end of the current cycle are equal to those at the end of the previous cycle, the integrated SI corresponding to the set of selected voltages at the end of the current cycle is judged to be the best-approximated SI for the target SI;

(6) when the integrated squares of difference at the end of the current cycle are not equal to those at the end of the previous cycle, steps 1 to 4 are repeated.

All operations required for these steps were automatically performed using spreadsheet software (Microsoft Excel, Microsoft Corp., USA) and a computer program developed in Visual Basic for Applications (Microsoft Corp., USA). A freeware data-transmission program module 'EasyComm' (http://www.activecell.jp/download/index.htm#EasyComm) was built into the program for sending voltage data from the computer to the DC power supply controller through RS232C ports. It takes approximately 10 s to perform all of the steps with a Pentium® IV laptop computer.

4. Testing of the Artificial Sunlight Source System

4.1 Single SI production

As an operational test for single (static) SI production, one-twentieth of the irradiance of GLS (1/20 GLS-CM) at noon on a clear day in May in Tokyo was produced (Fig. 5). In addition, 1/20 GLS-CM with both blue light (400-500 nm) increased by 25% and red light (600-700 nm) decreased by 50% and that with both blue light decreased by 50% and red light increased by 25% was produced (Fig. 6).

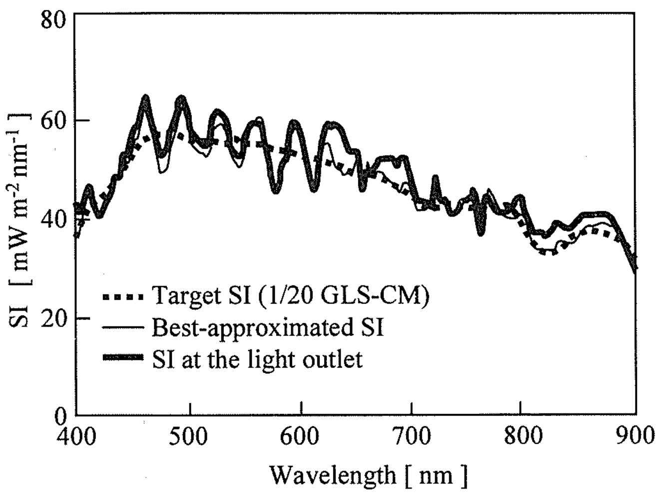


Figure 5 One-twentieth of the irradiance of ground level sunlight at noon on a clear day in May in Tokyo (1/20 GLS-CM; target SI), the SI best-approximating the target SI, and the SI at the light outlet produced by applying the set of selected voltages estimated to produce the best-approximated SI

The maximum irradiance produced by the artificial sunlight source system was less than one-tenth of GLS on a clear day at noon unless the standard rated forward voltages were applied on several LEDs. SI at the light outlet was produced by applying a set of selected voltages that had been estimated to produce the best-approximated SI, as discussed above.

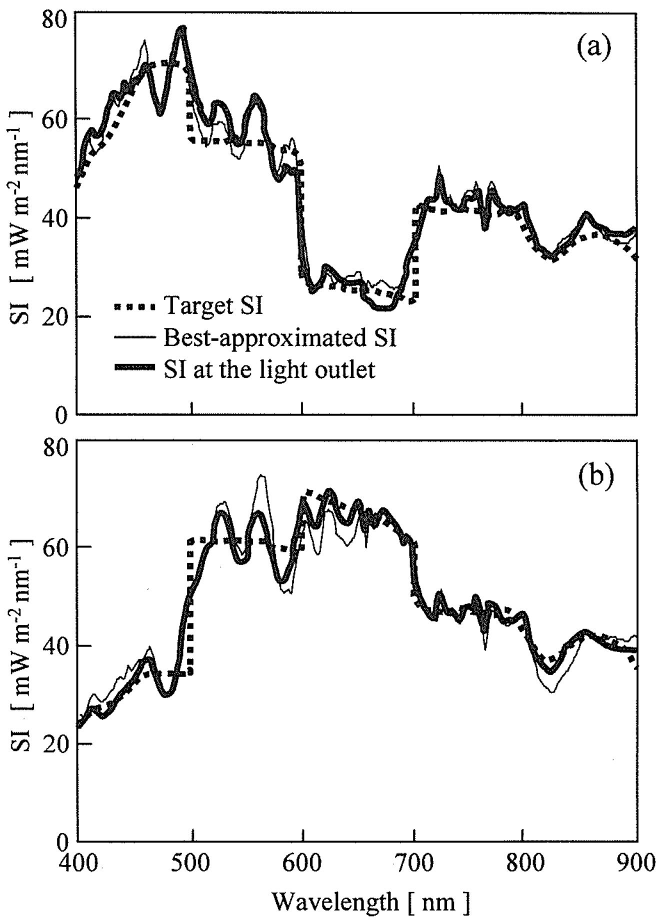
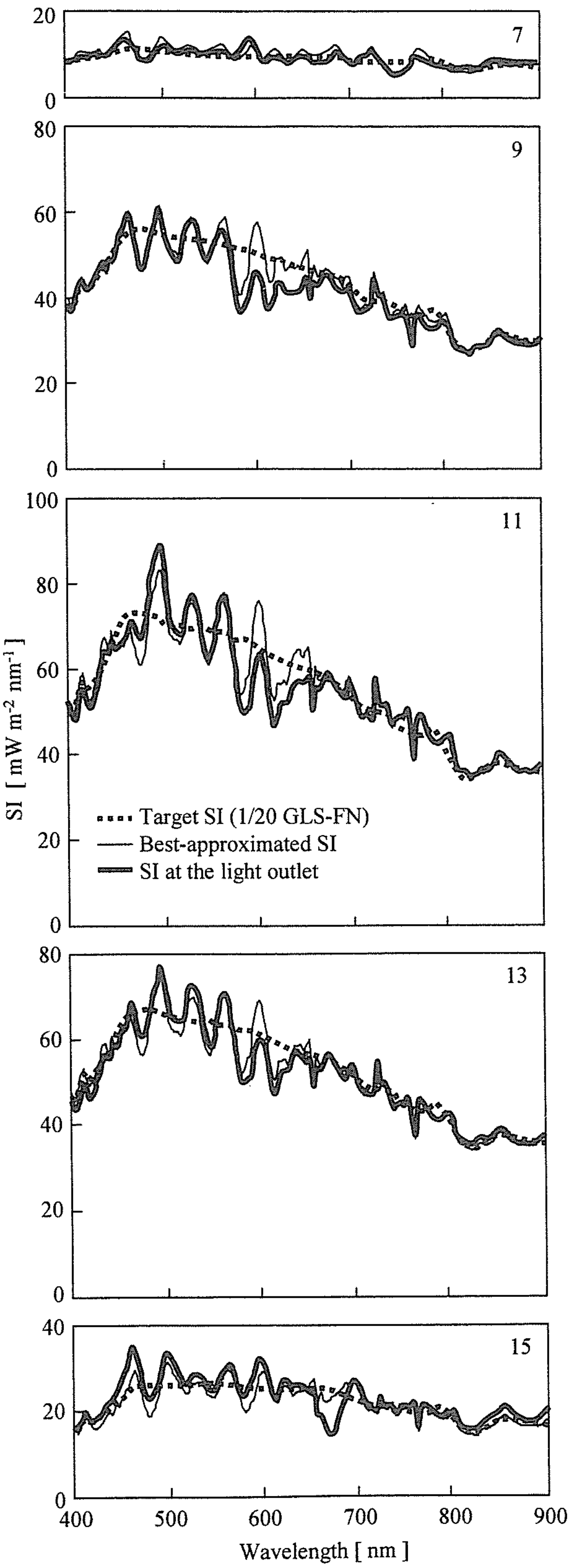


Figure 6 One-twentieth of the irradiance of ground level sunlight at noon on a clear day in May in Tokyo with both blue light (400-500 nm) and red light (600-700 nm) modified (target SI), the SI best-approximating the target SI, and the SI at the light outlet produced by applying the set of selected voltages that had been estimated to produce the best-approximated SI
(a) blue light increased by 25% and red light decreased by 50%; (b) blue light decreased by 50% and red light increased by 25%

Although there were small differences between SI at the light outlet and the target SI, the SI at the light outlet was quite close to the best-approximated SI for 1/20 GLS-CM with both the blue and red components modified. The small differences may be due to computing errors that occurred during construction of the voltage-SI database by linear interpolation of adjacent measured SI and/or differences in LED temperatures when measuring SI for each type of LED and production of the best-approximated SI. On the other hand, fairly large gaps were recognized for 1/20 GLS-CM with modified blue and red components where the curves for the target SI show a staircase pattern. This cannot be helped because spectral broadening with distance from the peak wavelength is a feature of irradiated light from LEDs.



4.2 Time-varying SI production

Time-varying (dynamic) SI can be produced by preparing a series of best-approximated SI. Because it takes almost 1 s to change SI from one value to another using this system, more than 1 s should be allotted as a time interval between two successive SI. As an operational test for time-varying SI production, we obtained a total of 5 GLS measurements at 2 h intervals between 7 and 15 o'clock on a fine day in November in Tokyo (1/10 GLS-FN) and then successively produced one-tenth irradiances of these 5 GLSs (Fig. 7) at 2 s intervals. The artificial sunlight source system operated as expected, producing time-varying light of the 5 GLSs.

The testing for the single and time-varying SI production demonstrated that the current system was capable of producing relative SPDs approximating GLSs and arbitrarily modified SPDs in a wavelength range of 400-900 nm in any order at 2 s intervals, although the irradiance was as low as less than one-tenth of GLS at midday of a clear day.

5. Necessary improvements to the system

Our goal is to develop an artificial sunlight source system capable of producing an SPD approximating GLS at any places on earth and capable of statically and dynamically producing arbitrarily modified SPDs. The most serious problem that confronts us is the low level of SPD or irradiance at the light outlet obtained using our system. In order to increase the level of irradiance at the light outlet, the following improvements may be considered: 1) utilization of higher power LEDs, 2) high density installation of LEDs on a circuit board, 3) increased light condensation efficiency with an improved conical reflection condenser, 4) utilization of a universal circuit board with high reflectance, and 5) utilization of several light source units each with an optical fiber bundle for guiding produced light to the object to be irradiated.

Figure 7 One-tenth irradiances of ground level sunlight obtained at 7, 9, 11, 13, and 15 o'clock on a fine day in November in Tokyo (1/10 GLS-FN; target SI), the SI best-approximating each target SI, and the SI at the light outlet produced by applying each set of selected voltages estimated to produce the best-approximated SI. The SI at the light outlet for each time point was produced successively at 2 s intervals by the artificial sunlight source system

If a sufficient level of irradiance at the light outlet can be achieved, for instance, the system should be capable of producing GLS from sunrise to sunset on the beach in Phuket (Thailand) and GLS through the night under the midnight sun at the lakeside in Helsinki (Finland), which no existing artificial light source can produce, although the wavelength range remains limited to 400 to 900 nm.

Another problem is increases in LED temperature during light production. We are considering installation of a heat sink on the backside of the LED module to keep the LED temperature constant. In addition, design of a printed-wiring board is under consideration to eliminate the spaghetti-wiring in the current device.

Acknowledgements

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