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# 3D intelligent supplement light illumination using hybrid sunlight and LED for greenhouse plants

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A B S T R A C T

This paper was aimed at coming up with a system that's used for the greenhouse plants with intelligent supplementary illumination, which can supply light to every leaf with a hybrid sunlight-LED (light-emitting diode) based on the Internet of Things (IOT). The system contained two light-supplement sections, one is the immediate sunlight lighting by fiber while made two generation novel sunlight collections of 0.225° sun-tracking precision, and skillfully solved the questions of the heat and multiple local point at fiber entrance, and another is LED lighting while designed a color LED belts for plants box central region illuminance of 2250lx and aside region of 1800-1350 lx where the illuminance uniformly covered 80% area. The system is designed for greenhouse plants by 3D supplementary lighting, which can be auto-switched to sunlight or LED at kinds of weather conditions, such as sunlight, weak sunlight, the cloudy and night. Experiment result shown the system could accelerate vegetables and fruits' growth rate, and the production of fruits and vegetables' is going to be much higher in the future. The 3D greenhouse frame with two layers has been grown vegetables by the supplementary lighting system. The intelligent lighting-switch system can be controlled by mobile with WiFi or bluetooth.

## 1. Introduction

Light is one of the most important environmental factors that affect the plant's growth and regulate its behavior. With the expeditious development of modern agriculture around the world, the requirement for obtaining year-round high production, good quality plants and off-season vegetables, fruits is highly demanded. Because of the foggy days, especially when the plants are growing at germination stage, they need adequate light illumination to finish their growth [1,2]. Therefore, in order to increase their production, supplementary lighting illumination is essential for greenhouse plants [3–5].

There are three methods for supplementary light: i) To open the scuttle and side window; ii) Using the light devices of mirror, light-guide fiber [6] and optical pipe [7,8] etc. to direct sunlight to shine plants; iii) Using artificial light source, such as incandescent lamp, halogen, fluorescent lamp, sodium lamp and LED (light-emitting diode), etc. A well-known statement of "All living things live from the Sun" is an eternal truth. The sunlight lighting has advantages of whole solar wavelength, organic, healthy, efficient, safe, energy-saving and emission reduction, etc [9,10]. The solar radiation (solar constant) is $1.74 \times 10^{17}$W/m$^2$ which equals to 17 bulbs of 100 W power. If the sunlight could be delivered directly for the lighting instead of converting it into electricity by solar panels, the utilization efficiency of solar energy will be greater than that of the electricity efficiency of solar panels. In some special circumstances, such as tunnels, mines, subways, underground parking, karst caves, underwater landscape, office buildings, hospitals, classrooms and greenhouse, they require illuminate all the day but the electricity sometime is not available.

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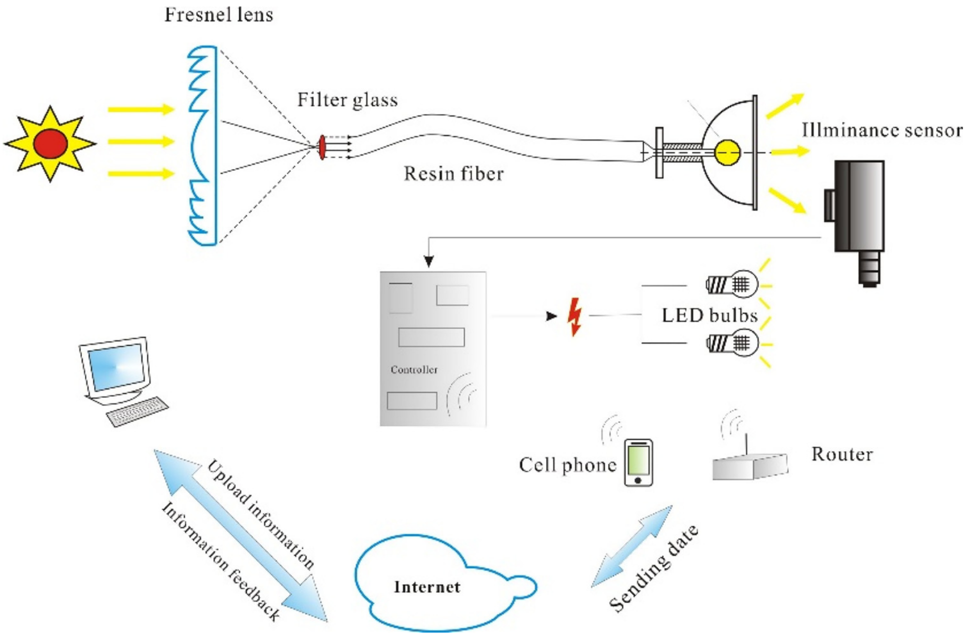



**Fig. 1.** Structure of hybrid intelligent illuminance by sunlight-LED based on IOT technology.

Although it is the fact that the bygone greenhouse plants used sunlight and LED [11–14] for lighting, we hope all the leaves are able to obtain sufficient light of effective spectrum from sunlight or LED. To build a natural light circumstance, we managed to decrease the shadow by adding more LED chips from 2 supplementary directions at least, made it as a shadowless growing space so that the plants can grow faster. Combining the advantages of sunlight and LED for the greenhouse plants, an intelligent sunlight-LED supplementary illumination system with multi-layers frame greenhouse plants has been proposed in our group. The plants can able to deliver sunlight directly in sunny and mild-sunny days, and LED lighting will be automatically switched on in cloudy days or during night-time. This intelligent lighting system can be auto-controlled.

This paper is organized as follows. Firstly, the sunlight-LED illumination design system as the whole article frame is first presented. Secondly, the optical technology details of the above-mentioned system are involved with the sunlight tracking and collection, sunlight transmission, abstract heat, auto-compensation lighting and auto-control lighting etc. Thirdly, some experiments are investigations. Finally, we get some conclusions.

## 2. Illumination requirement

The whole system of the hybrid intelligent lighting by the sunlight-LED based on the IOT is shown in Fig. 1. The system includes three major parts, including sunlight delivering device, LED supplementary part and wireless controller. When the outdoor sunlight is sufficient, the light can be collected by the Fresnel lens to converge outdoor sunlight through the optical fiber so that sunlight can be delivered into the greenhouse muti-layer plants directly. When the illuminance is lower, the installed illuminance sensor will switch on the LED lamps for additional plant lighting. Based on the IOT, the system connected with a Web browser, WiFi or Bluetooth on the smart mobile and it can help achieve the detecting and intelligent-controlled lighting.

Based on the illuminance system presented in Fig. 1, a new device profile of 3D greenhouse plants supplementary lighting by sunlight-LED is proposed. As illustrated in Fig. 2, there are four layers plants from the top to bottom. The sunlight shines the top layer plant directly, and the sunlight and LED can compensate to light the inside plants and every leaf for their different plants' PPFD (photosynthetic photon flux density) requirement. Approaching this way, 3D supplementary lighting can be achieved. Namely, during the plants growth, its every leaf can be illuminated between the lines of plants by the device. The 3D supplementary lighting is designed by LED lamps and shown in Fig. 3. A certain absorption wavelength can also be selected to illuminate the plant for its growing. For example, when the sapling is growing, it requires more light with the wavelength of 650 nm, and therefore compensatory lighting is supplied. The lighting condition of tomato is shown in Table 1 for its different grown time. For the bottom seedlings box of Fig. 3, the mixed color LED belts of red, blue and yellow are designed shown in Fig. 4. About Fig. 4 illuminance, there is the result which light intensity can satisfied the plants' light necessary shown in Fig. 5. The central illuminance is 2250 lx and the aside region is weaker about 1800-1350 lx which can be satisfied the supplementary requirement of illuminance uniformly covered 80% area.

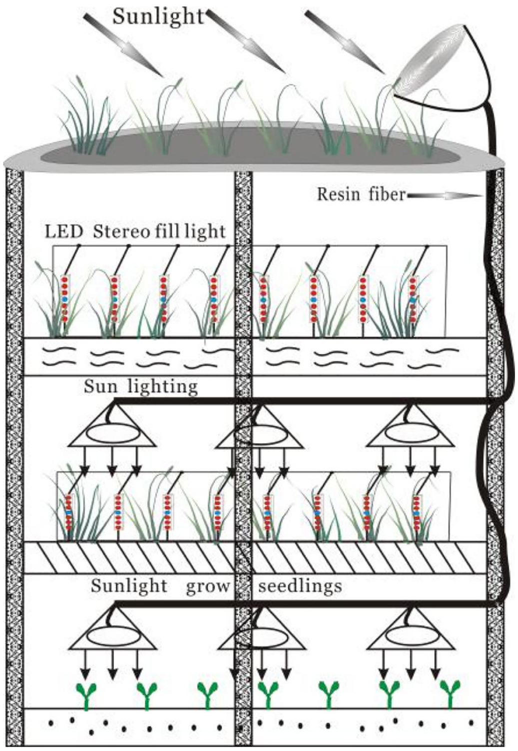



**Fig. 2.** Device profile of 3D greenhouse plants supplementary lighting by sunlight and LED.

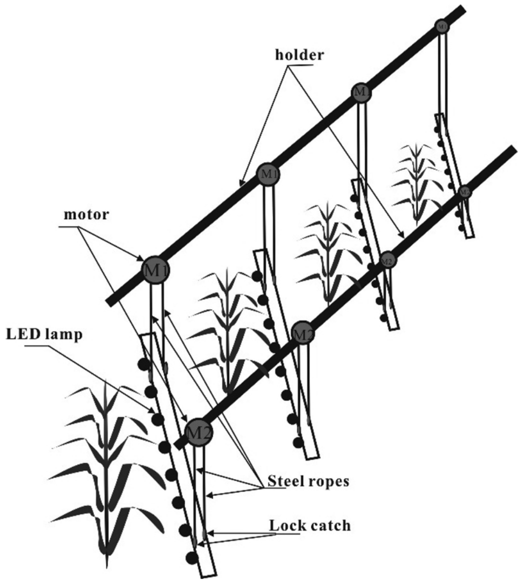



**Fig. 3.** Lighting the plant leaf between their lin es by LED lamps for 3D supplementary lighting.

## 3. Optical technology details

### 3.1. Sunlight tracking and collection

In order to light greenhouse plants by the sunlight, appropriate technologies for tracking and collecting the sunlight are essential shown in Fig. 6. The sunlight collecting apparatus should track the moving Sun. After calculating the characteristics of the solar zenith angle, sunrise and sunset time, latitude and longitude, etc. We fabricated two generation sunlight tracking devices shown as Fig. 7 for different environment conditions according to the structure illustrated in Fig. 1. In the first generation STACD (sunlight

**Table 1**
Supplementary lighting for tomato growth cycle.

| Conditions | Germination | Seedling | Blossom and yield fruit |
|---|---|---|---|
| Days(day) | 7–9 | 50 or so | 15–30 |
| Supplementary lighting wavelength (nm) | 630–680<br>450–480 | 630–680<br>450–480<br>597–577 | 630–680<br>580–595<br>450–480 |
| Appropriate light intensity(lx) | 40000–50000 | | |

**Fig. 4.** Arrangement for many LED belts source.

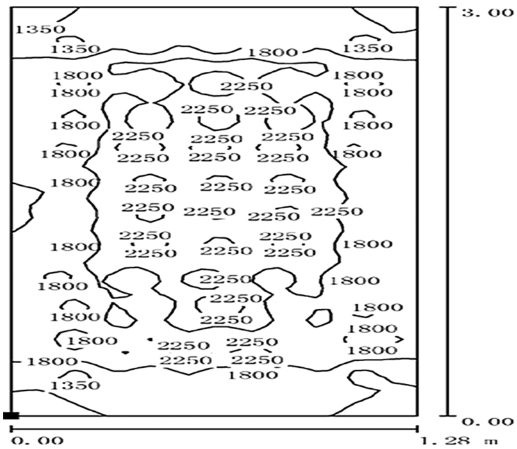



**Fig. 5.** Illuminance distribution under the necessity of Fig.4.

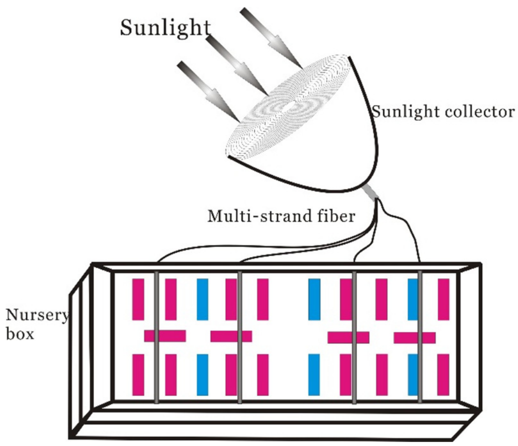



**Fig. 6.** Mixed sunlight-LED to light the seedling in nursery box for Fig. 2.

**Fig. 7.** Self-made two generation STACS.

tracking and collection devices) in Fig. 7 (left), the Fresnel lens is fixed at the fiber entrance of system, which has greater tracking precision, better heat dissipation, metal case, reliable cloud terrace, less noise, suitable for big core diameter fiber. It is suitable to be installed on the roof. However, the first generation STACD requires a larger installation space and 18–24 V alternating current, and has limited elevation and higher cost.

The second generation STACS is shown in Fig. 7 (right). The position of the lens inside the sphere is adjusted by Mecanum wheel, one direction of which is active wheel while the other perpendicular side wheels are passive. The Fresnel lens is fixed in the middle of two hemispheres and the sunlight tracking system is made with Arduino controller. The advantages of the second generation STACS are original, portable, and has a power dissipation 5–12 V alternating current, motion body embed and not be influenced by outside, plastic hull, lighter weight, less windage, etc. The disadvantages are less effective sunlighting areas, suiting for small core diameter fiber, limited torsion, some friction force, etc. Its lighting effect is less than the first generation. Through the test of our real system, the sun-tracking precision of the whole device can reach the same values of 0.225° in the components of altitude angle and azimuth angle, respectively.

A Fresnel lens as a sunlight collection component is used in two generation sunlight collecting systems as shown in Fig. 1. Although it's fabrication material poly (methyl methacrylate) PMMA (polymethyl methacrylate) has yellowing effect, the lens surface is coated with titanium dioxide antireflection which could effectively suppress yellowing. Fresnel lens has a low price and excellent optical performance.

### 3.2. Abstract heat and focal points question

There is very high heat at the entrance of fiber shown as Fig. 1, because the entrance is just at the focal point of Fresnel lens, the abstract heat question is skillfully solved by us. And because the polychromatic sunlight with different wavelength, so that a filter glass is also skillfully used to solve the multiple focal point after the Fresnel lens.

### 3.3. Sunlight transmission through fible

As shown in Fig. 1, the high power sunlight focused by the Fresnel lens must be transferred by an optical fiber. The transmission efficiency of the fiber must be stronger. In other words, optical transmission of fiber should be higher in our illumination system for the resin fiber. If the fiber transmission is known, the fiber length through the fiber can be determined. The nearly straight fiber loss relationship is expressed in eq.(1).

$$\mathrm{P}_{out}/\mathrm{P}_{in} = m = 10^{-\alpha L/10} \tag{1}$$

where $P_{\mathrm{in}}$ and $P_{\mathrm{out}}$ are the effective injection and injection optical fiber optical power respectively, $L$ is the length of the fiber, α is the fiber's attrition rate, $m$ is the ratio of optical power. According to Eq. (1), the near straight fiber transmission loss can be easily known. For some special building's lighting, the fiber needs to be bent indoor and it is therefore necessary to use the fiber bending loss equation as shown in Eq. (2).

$$\alpha = \frac{4.34W^2}{\beta a^2(1+W)} \times \left(\frac{U}{\upsilon}\right)^2 \exp\left[2W\text{-}\frac{2}{3}\left(\frac{W^3}{\beta^2 a^2}\right)\frac{R}{a}\right] \tag{2}$$

where $\beta = n_1 k_0 \cos\theta_z$, $U= a\sqrt{n_1^2 k_0^2 - \beta^2}$, $W= a\sqrt{\beta^2 - n_2^2 k_0^2}$, $\upsilon = \beta R$, $n_1$ and $n_2$ are the refractive index of the core and covering layer, $k_0$ is the wave number in vacuum, $\theta_z$ is the angle between the wave vector and z-axis, $a$ is the radius of the optical fiber core. According to Eqs. (1) and (2), a fluorine resin fiber core of acrylate copolymer of diameter of 8.8 mm, loss of 380 dB/km, numerical aperture of 0.6 was selected using ambient temperature of -30-70°C. The experiment results of fiber transmission are presented in Section 4.

### 3.4. Auto-compensation lighting

When the weather is cloudy or at night, the sunlight cannot provide sufficient illumination for plants, the system performs a function of the sunlight and LED lighting automatic switching. Combining Arduino board with BH1750 illuminance sensor, illuminance data is collected and processed to control the switch to adjust the indoor illumination. According to different lighting spaces, an illuminance threshold is designed in our system. If the sunlight cannot reach this threshold, the system will automatically be switched to control the relay LED lighting. For example, if the indoor illumination threshold is selected as 400 lx, the sensor will detect whether the illumination data is beyond 400 lx. If the sunlight lighting illumination is below 400 lx, the system will automatically turn on LED lighting to compensate sufficient intensity for plants. The closed control relay can make the indoor illumination to be 400 lx at least. In addition, it is due to different needs of plants light intensity, we need to simulate the distribution of light intensity around every layer of 3D greenhouse plant by software. For example, for a nursery box shown in Fig. 4, the simulating result of LED for the light intensity distribution is shown in Fig. 5. The lighting intensity of the 3D seedling greenhouse plants' box could be simulated with an illuminance of 2250 lx and covered the box's 80% area.

### 3.5. Autocontrol lighting

Using the technology of internet of things (IOT) to release the auto-management for the greenhouse plants's illuminance makes the system easy and high efficient. The purpose of the system shown in Fig. 1 is to realize intelligence greenhouse agriculture designed by wireless communication network and the automatic control to meet the growing condition of the plants. The hybrid intelligent lighting systems of sunlight-LED is put forward to the lighting of greenhouse plants based on IOT technology shown in Fig. 8. This system is capable of detecting and adjusting greenhouse's parameters such as lighting intensity, temperature, humidity, greenhouse rolling screen, dropping irrigation by IOT. The intelligent illumination system shown in Fig. 8 can be integrated by the respective advantages of Zigbee, WiFi, wireless network nRF24l01 and realize the information collection for indoor illumination and instruction control by Yeelink matter networking platform. The system can also meet the intensity of illumination standard of plant growth by closed-loop control and real-time adjustment. Users can select the types of terminal devices which equipped with a Web browser, WiFi, Buletooth or mobile capability to achieve the control of the lighting and the others.

## 4. Experiment tests and results

### 4.1. Exp. 1 vegetable growing results

According to the designed system of Figs. 1 and 2, the prototype of the real objects for the above-mentioned hybrid sunlight and LED illumination shown in Fig. 9 was fabricated and used for performance test. The sunlight lighting system and its electric lighting switch can be controlled by IOT's supporter. The hand-held mobile in the lower right corner of Fig. 9(a) could control the switch of

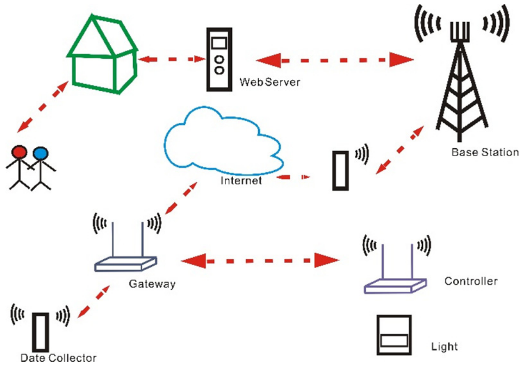
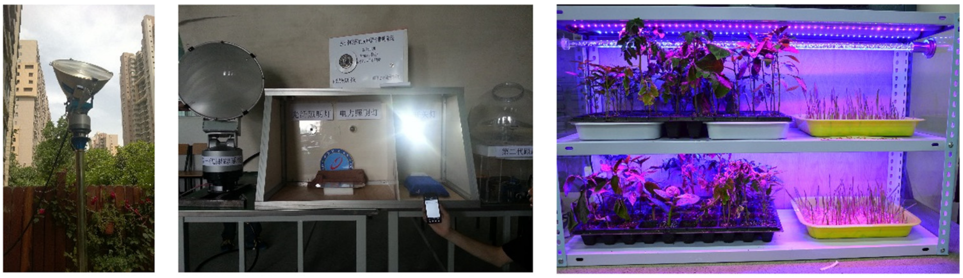



**Fig. 8.** IOT control system for the hybrid lighting of sunlight and LED and the others.



(a) (b) (c)

**Fig. 9.** 3D sunlight and LED lighting prototype and real objects. (a)Sunlight tracking collector installed on the back yard for indoor plant illumination in Fig. 1. (b).Hand-held mobile (right lower) could control the intelligent switch for the sunlight and LED lighting. (c) Real objects of Fig. 2 delivered by the sunlight with optical fiber and scatter the beam in the nursery box which sunlight is collected by Fig. 9(a). The bottom plants are lighted by the sunlight directly; the upper plants are lighted by the hybrid sunlight and LED belts which can be controlled according to plants' light requirement for different time and season. The vegetable is growing rapidly.

sunlight and electric lighting which was equipped with a WiFi-enabled devices and modules. The bottom plants of 3D potted plant aere lighted by the sunlight and LED hybrid lighting according to plants' light requirement for different time and season. The vegetable was growing rapidly shown as Fig. 9(b).

### 4.2. Exp. 2 fiber transmission ratio

The sunlight is leading-in the 3D greenhouse for illuminating the multilayer plants by optical fiber. The fiber may be bended according to different plants frames. The fiber's transmission ratio for the near straight, microbended and macrobended fiber for the different plant's lighting usage should be tested. These fiber's transmission ratio about the near straight, microbended and macrobended fiber are obtained shown in Tables 2, 3 and 4 . The results of average optical power transmission ratios of near straight fiber are 0.28, 0.44, 0.36 and 0.31, the microbending fiber average transmission ratio is 0.40, and the microbended fiber transmission ratios are 0.28-0.40. The results of fiber transmission ratio can help to build the multilayer plants' illumination reference.

### 4.3. Exp.3 Illuminance test for the sunlight lighting

In order to compare the illuminance result between our sunlight lighting system and the electric lamp lighting, the experiment of illuminance comparison between the sunlight and electric lighting of 100 W power lamp is designed. The experimental conditions used are Fresnel lens diameter of 40 cm microbending fiber, and power meter range is 20 mW, fiber length is 3 m, fiber core diameter is 6 mm, and spotlights lamp rated power is 100 W. The illumination detection distances between luminometer and the source is 30 cm for spotlights lamp and fiber sunlight lighting system (Fig. 1). The illumination test comparison results are shown in Table 5. The average illuminance of $2.80 \times 10^4$ lx for sunlight is brighter than 100 W spotlight illuminance of $2.23 \times 10^4$ lx. This obvious advantage result of direct sunlight lighting without photoelectric conversion can be used to lighting not only for planthouse, but also for the locations of tunnel, the underground parking garage, the subway, and schoolroom etc. which need lighting in daytime with the bright sun. This is a very large market which the sunlight is used to lighting directly.

## 5. Conclusions

The sunlight with its advantage of green, safe, environmental friendly can be used for direct lighting. A 3D supplementary hybrid

**Table 2**
Test transmission ratios of near straight fiber for the sunlight lighting.

| group | fiber angle of elevation(°) | Power (mW) | Measurementvalue | | | |
|---|---|---|---|---|---|---|
| 1 | 15 | Input | 0.57 | 0.60 | 1.22 | 1.01 |
| | | Output | 0.17 | 0.2 | 0.31 | 0.26 |
| | | *m* | 0.30 | 0.33 | 0.25 | 0.26 |
| 2 | 30 | Input | 1.10 | 1.04 | 1.07 | 1.04 |
| | | Output | 0.47 | 0.44 | 0.43 | 0.52 |
| | | *m* | 0.43 | 0.42 | 0.40 | 0.5 |
| 3 | 45 | Input | 0.92 | 0.91 | 0.92 | 0.93 |
| | | Output | 0.27 | 0.29 | 0.37 | 0.38 |
| | | *m* | 0.29 | 0.32 | 0.40 | 0.41 |
| 4 | 60 | Input | 0.46 | 0.48 | 0.49 | 0.48 |
| | | Output | 0.16 | 0.15 | 0.14 | 0.15 |
| | | *m* | 0.35 | 0.31 | 0.28 | 0.31 |

**Table 3**
Transmission ratios of microbending fiber for the sunlight lighting.

| | | | | | | |
|---|---|---|---|---|---|---|
| Input power $P_{in}$(mW) | 4.06 | | | | | |
| Output power $P_{out}$(mW) | 1.57 | 1.58 | 1.65 | 1.61 | 1.62 | 1.67 |
| $m = P_{\rm out}/P_{\rm in}$ | 0.39 | 0.39 | 0.41 | 0.40 | 0.40 | 0.41 |

**Table 4**
Macrobending fiber transmission ratios for the sunlight lighting.

| | | | | |
|---|---|---|---|---|
| Input power $P_{in}$(mW) | 4.06mW | | | |
| Macrobending angle( $^\circ$ ) | 360 | 720 | 1080 | 1440 |
| Output power $P_{out}$(mW) | 1.45-1.50 | 1.35-1.40 | 1.30-1.35 | 1.30-1.35 |
| $m = P_{\rm out}/P_{\rm in}$ | 0.36-0.37 | 0.33-0.34 | 0.32-0.33 | 0.32-0.33 |

**Table 5**
Illumination comparison test results for sunlight lighting and 100 W spotlights.

| | | | | | |
|---|---|---|---|---|---|
| Spotlight electric illuminance ( $\times 10^4$lx) | 2.12 | 2.32 | 2.25 | 2.22 | Ave = 2.23 |
| Fiber sunlight illuminance ( $\times 10^4$lx) | 2.37 | 3.31 | 2.68 | 2.85 | Ave = 2.80 |

intelligent lighting system with the sunlight-LED for growing the greenhouse plants is put forward and designed in this paper.

According to the simulated results of 3D seedling greenhouse plants' box which can be well-distributed light requirement to be 2250 lx and covered the box's 80% area, a greenhouse frame with two layers' plants was fabricated to grow vegetables by sunlight and sunlight–LED mixed supplement lighting respectively.

Two generation sunlight tracking collectors were made for different buildings. The first one used the traditional resin Fresnel lens for sunlight collecting and transferred to lighting by resin optical fiber and the second one was designed innovatively according to Mecanum wheel characteristic which can reach the same values of 0.225° in the components of altitude angle and azimuth angle.

The experiment results are shown that the two layers frame greenhouse vegetable grew madly under our hybrid sunlight and LED supplement lighting illumination system. The intelligent lighting auto-switching for the sunlight and LED lighting at the weak sunlight, cloudy days or night according to different illumination conditions are able to work wirelessly by WiFi, mobile, bluetooth etc IOT technology. The average transmission ratios of optical fiber for transferring sunlight of straight and microbended are to be 0.28-0.40. The average illuminance of $2.80 \times 10^4$lx for the sunlight lighting system with a 40 cm diameter Fresnel lens is brighter than 100 W spotlight illuminance of $2.23 \times 10^4$lx.

This hybrid intelligent supplement lighting system overcomes the disadvantages of traditional photovoltaic lighting system which influenced by time and weather, and prevents adverse impact of indoor lighting. This lighting system is not only suited for greenhouse plants lighting, but also for the places of indoors, basement, underground, etc.

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