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Article

A brief analysis of spectral technology for effective utilization of full spectrum of solar energy

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Abstract: In this paper, a spectroscopic technology based on a trough-type parabolic condenser is proposed, which effectively utilizes the full spectrum of solar energy for light transmission through optical fibers. The technology comprises four parts, which are concentration, transmission, splitting, and detection, and its application in the field of clean energy was explored. A one-way glass is introduced into the installation as a device for light transmission restriction. The one-way transmittance of one-way glass effectively ensures the transmission direction of sunlight. According to the light simulation results from TracePro software, after the light was transmitted through the one-way glass reflection device, light intensity was guaranteed to meet usage requirements. After being focused by collimating lens and Fresnel lens, the light is introduced into a Roland circle spectroscopic system through an optical fiber. After splitting, various types of light passing through the detection system are introduced into their respective optical fibers for long-distance transmission and use. From the experiments, it was found that through reasonable splitting and the targeted use of different wavelength bands, the effective utilization of the full spectrum of solar energy significantly improved, verifying the feasibility of the device design idea.

Keywords: full spectrum of solar energy; new trough-type solar energy collection and light transport device; optical fiber; Roland circle spectrometry; spectroscopic utilization

1. Introduction

With the continuous development of society, the demand for energy consumption is increasing. At present, the world's energy is still dominated by traditional fossil energy, which has led to increasingly serious environmental problems [1–3]. Since China proposed the "dual carbon target" in 2020 [4], the green and low-carbon transformation of energy is imminent [5]. Solar energy, which is green, clean, abundant, and renewable, has great development potential for replacing fossil energy [6–9]. In addition, as a full-wavelength radiation energy, it has tens of thousands of absorption lines and emission lines and is an extremely rich treasure trove of solar information. About 99.9% of the energy in sunlight is concentrated in the ultraviolet (UV), visible light, and infrared (IR) regions. The ultraviolet region is widely used for disinfection and promoting certain chemical reactions, such as photocuring, due to its bactericidal properties. The visible light region is the basis of human vision and plant photosynthesis and is also the key band for solar panels to convert light energy into electrical energy. The infrared region shows its importance in the fields of thermal energy collection, night vision technology, and remote sensing detection, such as in the applications of infrared thermal imagers and solar water heaters. These applications reflect the good prospects of the utilization of sunlight in different bands. However, the current ways to utilize the full spectrum of sunlight are mainly via photovoltaic-thermoelectric, photovoltaic waste heat–thermal cycle, and photovoltaic waste heat utilization [10]. It can be seen that the current ways of utilizing solar energy are relatively limited. Based on the above background, in this paper, in order to increase the effective utilization of solar energy and improve the utilization of this clean energy as much as possible, we analyzed the full spectrum characteristics of solar energy, performed light transmission loss and grating spectroscopic principle analyses, and proposed a new spectroscopic technology for the effective utilization of the full spectrum of solar energy, where the technology includes a focusing part, a transmission part, a spectroscopic part, and a detection part. A Roland circle was used as the basic element in the spectroscopic part. The purpose of this technology is to make full use of sunlight of different wavelengths so as to further improve the effective utilization of solar energy and promote the green and low-carbon transformation of energy.

2. Technology for effective conversion of full spectrum of solar energy

As shown in **Figure 1**, the overall technical route of the spectral technology for the effective utilization of the full spectrum of solar energy is demonstrated, which comprised four parts—the focusing part, transmission part, spectral part, and detection part—covering the processes of solar energy collection, introduction, spectroscopy, and detection, respectively. After research, a trough-type solar energy collection device is used due to its advantages, such as a high concentration ratio and high precision, to provide a high-quality and sufficient source of sunlight for subsequent use. Optical fiber transmission is used for the transmission process. Then, based on the grating spectral principle, the visible light, ultraviolet light, infrared light, and various rays with different properties in the sunlight are introduced into different light guides. After correct detection, subsequent use of the light spectrum can be carried out, hence fully improving the utilization efficiency of solar energy.

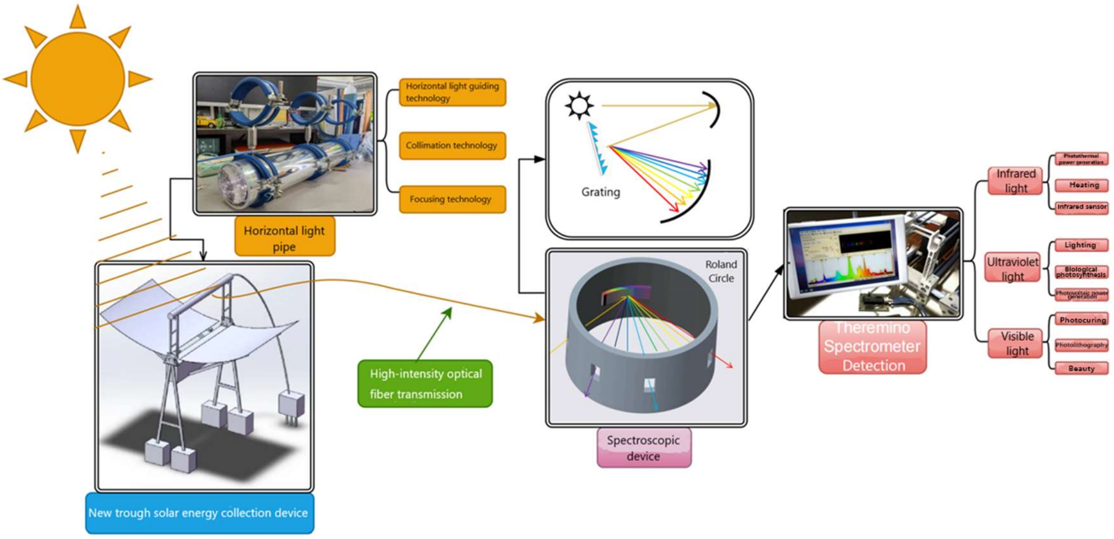

Figure 1. Overall technology roadmap.

2.1. Solar energy capture and light transport

According to optical principles, solar concentrators can be divided into refractive, reflective, hybrid, fluorescent, thermophotovoltaic, and holographic types [11]. In daily applications, reflective and refractive solar concentrators are more widely used. Reflective concentrators mainly include parabolic concentrators, which are divided into three types: trough solar concentrators, dish solar concentrators, and compound parabolic concentrators. Transmissive solar concentrators mainly include Fresnel concentrators [12]. Considering the low cost and high solar-energy utilization of trough solar concentrators, we built a new trough solar energy collection and transportation device based on trough solar concentrators. The device is mainly composed of trough parabolic concentrators, horizontal light-guide tubes, one-way glass, TIR collimating lens, Fresnel lens, and optical fibers.

2.2. New trough-type device for solar energy gathering and light transport

The device is mainly divided into the focusing part and the light transport part. The focusing part is composed of a trough parabolic concentrator, a rack, and a tracking system. The trough parabolic concentrator is the core of the entire system. The reflector generally has the characteristics of high precision and high reflectivity to ensure the focusing efficiency of the device. After an optical path simulation analysis and comparison, we used a reflector with a thick glass surface to ensure solar energy focusing efficiency. The depth of the parabola is 370 mm, the width is 1470 mm, and the focal distance is 850 mm from the vertex of the parabola. As the sun moves at all times, for light simulations at different times, a GZW-1 control system is used as the core control system, and a shading solar tracking system arranged in the east-west direction and tracked in the north-south direction has been configured. The two form a closed-loop control to ensure tracking accuracy and improve the utilization efficiency of solar energy.

The transmission part comprises three parts: a unidirectional light guide system, an optical fiber transmission system, and a collimation system. After the trough reflector focuses the light on its axis, the light will maintain its original direction, and the light gathering points are arranged linearly. If the light is directly collected and utilized, the collection cost is extremely high. In order to improve the utilization rate of light beams and control the collection cost, a tubular light guide device was selected to change the direction of light from longitudinal diffusion to lateral transportation, constrain the light transmission path, and improve collection efficiency.

The installation process of the new trough solar energy collection and transportation device required a one-way glass placed in the horizontal light-guide tube, with the one-way glass mirror’s surface facing the center of the tube. The inner wall of the light guide tube above the one-way glass is covered with a reflective film with a high reflective coating. The device is shown in **Figure 2**.

Figure 2. New type of trough solar photovoltaic composite device.

After the trough solar parabolic mirror focuses the sunlight on its axis, the light passes through the light tube with the single-sided glass element, and the direction of the light changes from longitudinal diffusion to lateral transportation, and hence the light transmission path is restricted. A TIR collimating lens is installed at the exit of the light tube. For light beams in the area of a large divergence angle, collimation optimization is performed by reflecting the light on the lens' glass wall; for light beams in the area of a small divergence angle, a method similar to lens transmission has been adopted, where the light is collimated by refraction through the lens. A Fresnel lens is installed at the port of the TIR collimating lens. The collimated light beam passes through the Fresnel lens to achieve a focusing effect, increase light intensity per unit area, and improve the efficiency of light energy utilization. Finally, the light beam focused into a point is introduced into optical fibers for long-distance light transportation. The three-dimensional renderings of the device are shown in **Figure 3**.

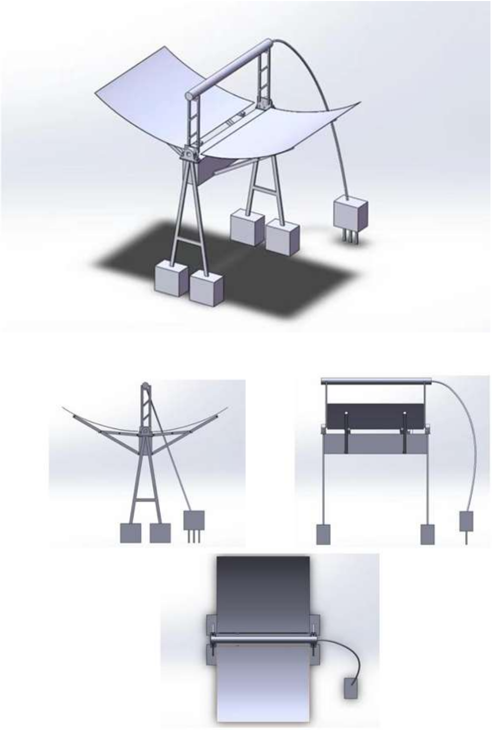

Figure 3. Three-dimensional schematic diagram of novel trough device for solar energy capture and light transport.

The sun's rays are parallel to the axis of the parabola and incident on the reflector's surface, while the parabolic reflector structure reflects, gathers, and emits the incident light, which is the focal line of the trough's parabola. The focusing ratio of the parabolic reflector mainly depends on the aperture ratio of the trough's structure, that is, the ratio of the diameter of the incident light and the focused light at the geometric focus. With the vertex of the bottom of the parabola as the origin and the center line as the image ordinate as the axis to establish a coordinate system, the equation of the parabola is $x^2 = 2py$, and the focal coordinate of the parabola is F（$\frac{p}{2}$， 1）. The light path diagram of the trough reflector was simulated using the TracePro software. As shown in **Figure 4**, light is projected vertically onto the parabola and focused at the intersection of the parabola at the upper end after being reflected by the mirror.

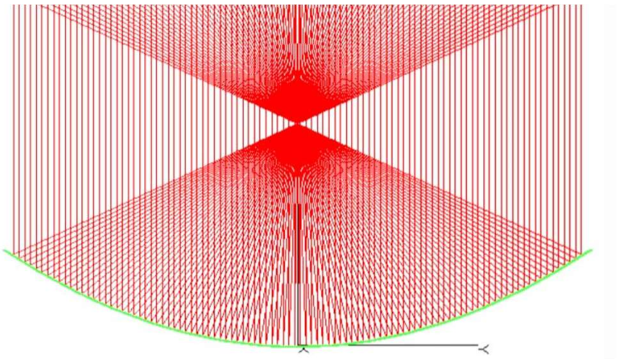

Figure 4. Schematic diagram of simulation of parabolic optical path.

In actual application, sunlight enters the reflector obliquely. TracePro was used to simulate the solar azimuth from 10:00 to 14:00 Beijing time, and the parabola-focusing situation was analyzed at 45°, 60°, and 75° of sunlight (see **Figures 5–7**).

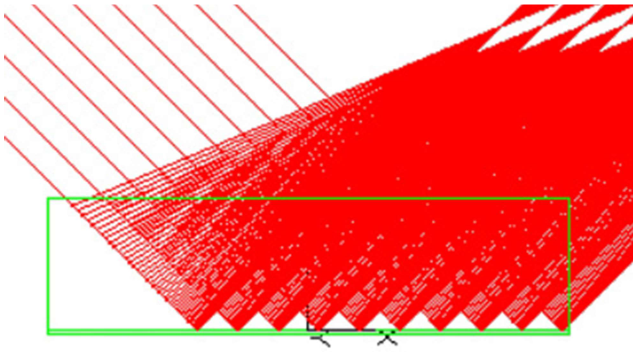

Figure 5. Condenser concentrator's effect at 45° of sunlight.

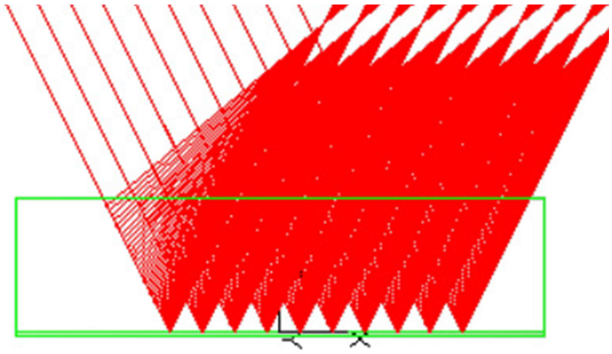

Figure 6. Condenser concentrator's effect at 60° of sunlight.

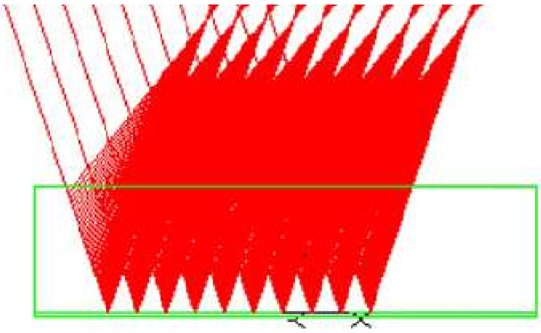

Figure 7. Condenser concentrator’s effect at 75° of sunlight.

It can be seen from the simulation diagrams that when the new trough-type solar energy collection and light transport device was arranged in the east-west direction and tracked in the north-south direction, and when the sunlight was projected into the concentrator at any angle, the light was always focused at the height of the parabola’s focal line and the focusing effect was stable. The feasibility of using the trough concentrator was verified.

In the transmission of light beams, irreversible loss of light energy is inevitable [10]. Therefore, in the design of the light transport system, reducing energy transmission loss should be given priority.

The one-way light guide system mainly consists of a light guide tube and a one-way glass. The inner wall of the light guide tube is covered with a high-reflectivity coating to minimize absorption and dissipation that may occur during the light transmission process. **Figure 8** shows the schematic diagram of the light guide tube. However, a traditional light guide tube cannot be directly applied to the trough concentrator. It was necessary to integrate and constrain the light and improve it by adding a one-way glass.

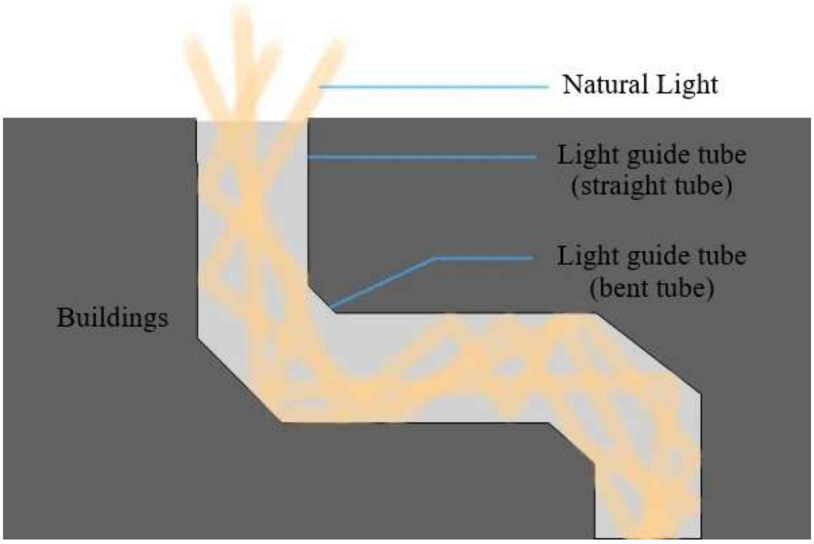

Figure 8. Schematic diagram of light guide device.

The optical properties of the selected one-way vision glass are shown in **Table 1**.

Table 1. Optical properties of unidirectional see-through glass.

Optical performance	Light transmittance			Albedo	
	Visible light	**Ultraviolet**	**Total solar energy**	**Visible light**	**Total solar energy**
Mirror	5%	2%	16	93%	30
Glass surface	85%	28%	16	10%	6

After measurements, the focusing spot of the trough parabolic reflector was about 10 mm. To ensure that the spot of this width was incident on the center of the emitting tube, a 50mm-wide one-way glass was installed in the light guide tube, as shown in **Figure 9**. The light path simulation diagram in the tube is shown in **Figure 10**. After the integration of the device, a higher amount of usable light energy was obtained at the output end of the light guide tube.

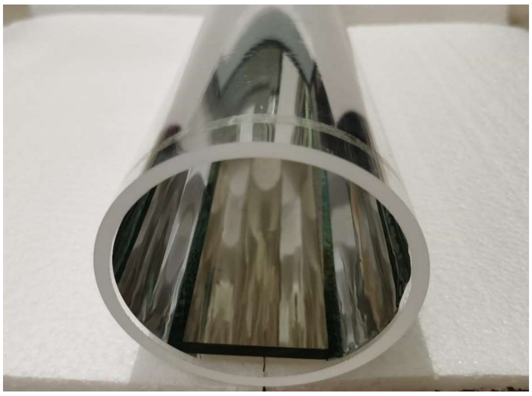

Figure 9. Image of inside of light guide.

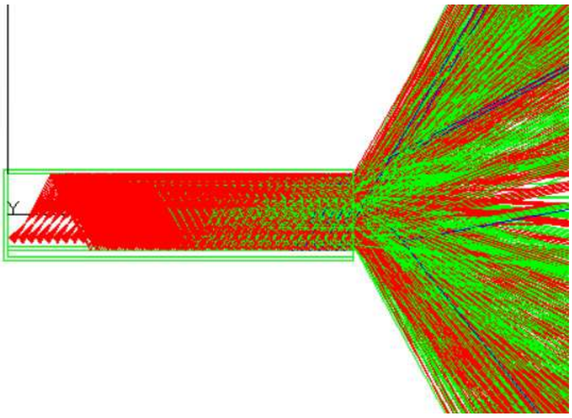

Figure 10. Schematic diagram of optical path simulation in light guide.

Light is collected by the light guide tube to the output end and then transmitted through an optical fiber. It can be concluded that the transmission efficiency is different, as light enters the optical fiber at different angles. Therefore, the light at the output end is collimated and then further utilized. The TIR lens performs collimation and focusing, which improves the transmission efficiency of the optical fiber. From the grating diagram, after collimation, it can be seen that the TIR lens effectively improved the light intensity and light energy utilization efficiency per unit area. In addition, the light intensity distribution at the exit end was more uniform, and the unit light intensity was higher (**Figure 11**).

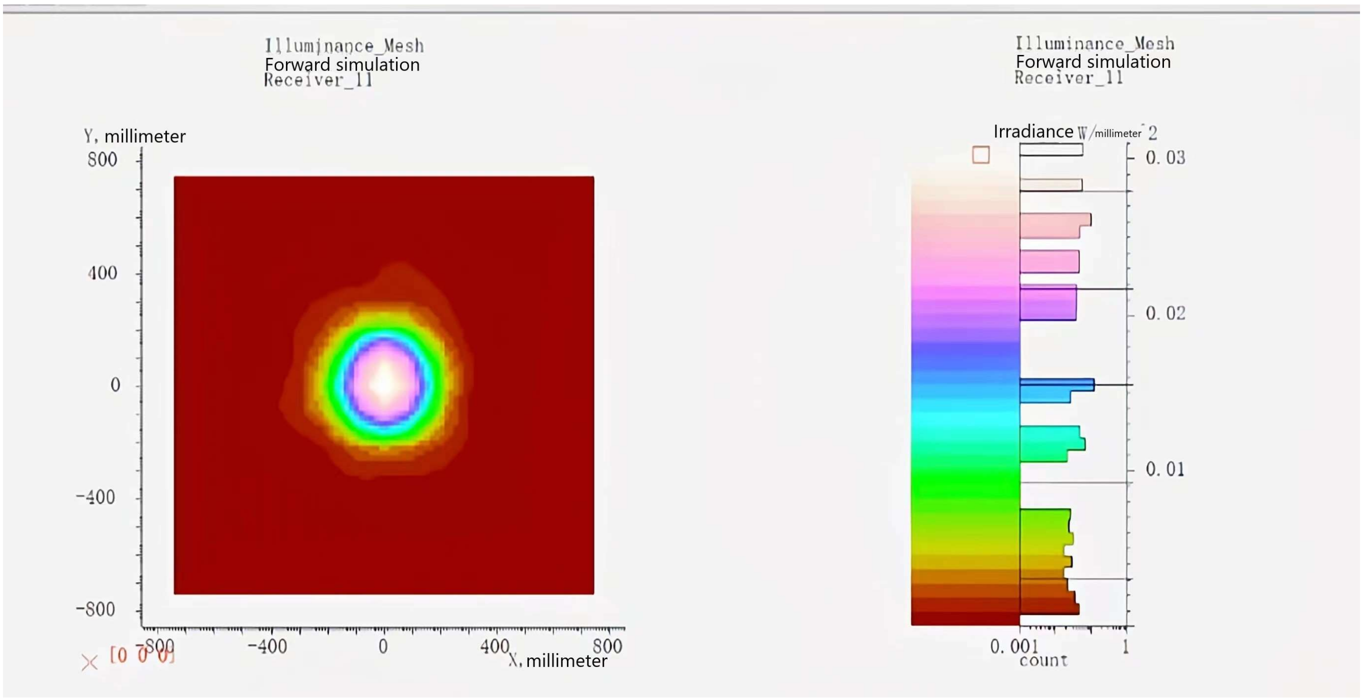

Figure 11. Raster diagram after collimation through TIR lens.

Figure 12 shows the light transport effect. It can be seen that there was a light spot due to light coming out from the exit end, proving the feasibility of the technical route.

Figure 12. Beam transmission.

2.3. Spectroscopic and detection systems

The solar spectrum refers to the characteristics of solar radiation distribution by wavelength. It can be divided into radio waves, infrared rays, visible light, ultraviolet rays, and rays (such as X-rays), of which visible light can be divided into seven colors: red, orange, yellow, green, cyan, blue, and purple. The wavelength range where solar radiation energy is most concentrated is 0.2–4 μm. Due to the absorption of ozone, water vapor, and other substances in the earth's atmosphere, solar radiation with wavelengths below 200 nm and above 2500 nm basically cannot reach the ground. The solar radiation bands that can reach the earth's surface mainly include ultraviolet light of 250–400 nm (accounting for 7% of energy), visible light of 400–760 nm (50% of energy), and near-infrared light of 760–2500 nm (43% of energy) [13,14]. However, in daily applications, the development and utilization of solar energy mostly stays in the visible light part. For this reason, in this study, it was proposed to divide sunlight into three parts, which are infrared light, visible light, and ultraviolet light, and use sunlight in a step-by-step manner to improve the effective utilization of sunlight.

The concentrated and transmitted sunlight was split, and the separated light was verified after the splitting was completed and finally guided to the utilization end using the same transmission system.

2.3.1. Spectroscopic system

The characteristic of a Roland circle optical structure is that the center of the concave diffraction grating and the incident slit are both placed on a circle with a diameter equal to the radius of curvature of the concave grating surface, and the spectrum after dispersion by the concave diffraction grating will also be focused on the circle [15]. After being collimated and focused by a collimating lens, the light enters the slit and is then projected onto the concave diffraction grating. The concave grating uses the dispersion effect to disperse light of different wavelengths and then uses the focusing effect to focus light of the same wavelength onto the Roland circle [16]. The designed Roland circle spectroscopic structure is shown in **Figure 13**. The spectroscopic introduction detection system can be completed by connecting the light guide device at the corresponding position of the Roland circle, as shown in **Figure 14**.

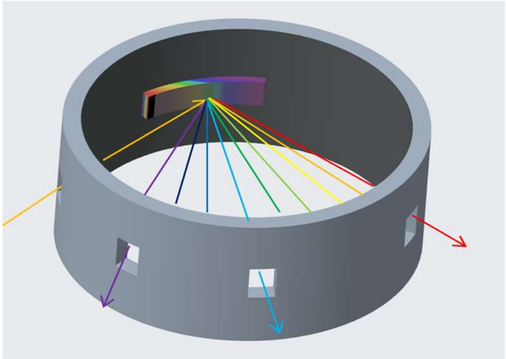

Figure 13. Configuration of Roland circle spectroscopic structure.

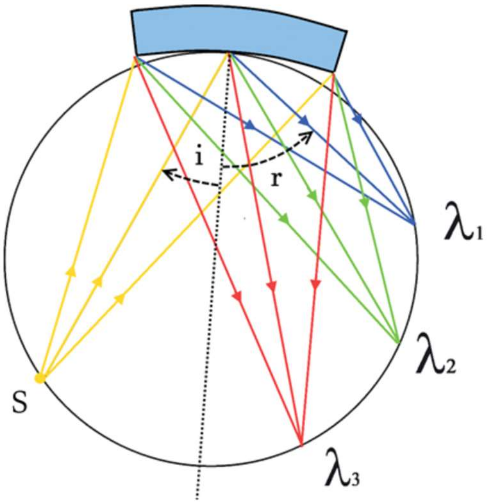

Figure 14. Rendering of Roland circle spectroscopic light.

2.3.2. Detection system

Via the Theremino Spectrometer software, the light signal is converted through electronic circuits. The separated light is introduced into a spectrograph instrument and transmitted to a communication instrument through a USB communication interface for spectral analysis. The spectrum is then visualized by the software and compared with the expected spectrum image. In this study, the spectrum characteristics of different light sources were compared and ultraviolet light, visible light, and infrared light were distinguished so as to detect the effect after spectral separation.

Ensuring the correctness of the entire technical route was important. Before the application of the device, the analysis results needed to be calibrated. A more convenient fluorescent lamp was used. The calibration spectrum is shown in **Figure 15**. The tips of the two mercury characteristic peaks at 436 and 546 nm were adjusted. After calibration, the analysis software of Theremino Spectrometer was used to perform quality inspection to confirm the spectral effect.

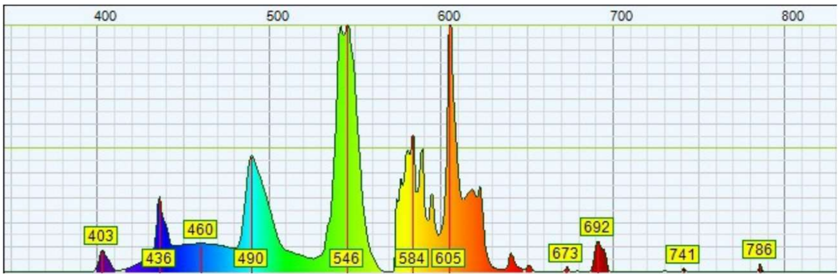

Figure 15. Fluorescent light calibration spectrum.

3. Conclusion

When the sun’s rays are projected into the new trough concentrator at any angle, the simulation experiment verified that the rays were always focused at the height of the parabola focal line and that the focusing effect was stable, which verified the feasibility of the trough concentrator.

The one-way perspective glass was added to the light guide device as a core component so that light enters the light guide from the side. The one-way light transmittance of the one-way perspective glass overcame the constraint on the propagation of the solar beam and converted the laterally diffused solar beam collected by the trough concentrator into longitudinal transmission so that the advantage of the high concentration ratio of the trough concentrator can be applied in the refined utilization of solar energy.

After the light at the output end was collimated and focused by the TIR lens, the light entered the optical fiber at a suitable angle, which improved the utilization rate of the collected light energy and further improved the utilization of sunlight. In addition, the light intensity distribution at the outlet end was more uniform, ensuring the efficiency of solar fiber transmission.

The spectrometer used a Roland circle optical structure to manipulate the focused light. After the device was tested using the Theremino Spectrometer software, the feasibility of the overall technical route was ensured.

Author contributions: Model design, GY and ZM; simulation, GY and ZM; experimental verification, GY and ZM; data calculation, RN; writing—original draft preparation, GY and ZM; device design and processing, XJ; writing—review and editing, XJ; supervision, XJ. All authors have read and agreed to the published version of the manuscript.

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