Spectral Beam Splitting Technology for Photovoltaic and Concentrating Solar Thermal Hybrid Systems: A Review

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Abstract: As a promising technology, spectral beam splitting (SBS) technology is the research focus currently in photovoltaic and concentrating solar thermal (PV/CST) hybrid systems. Spectral splitting filters can optimally exploit the solar spectrum and reach higher conversion efficiencies of solar energy. In this paper, we provide a review of the recently published research in spectral splitting filters and summary the research details of SBS technology, including the proposed methods, types, materials, performance advantages, technical obstacles of the filters. Moreover, the paper presents the research status of the SBS technology and evaluates the prospects of various filters in PV/CST hybrid systems. This review can help the researchers and practitioners better understand the SBS technology and features of different spectral splitting filters for the PV/CST hybrid system.

Keywords: Photovoltaic; Concentrating solar thermal; Spectral beam splitting; Spectral splitting filter; Optical performance.

1. INTRODUCTION

Traditional fossil energy resources use the account for about 80% of global energy, but it is not inexhaustible [1]. Energy and environmental crises have motivated the development of renewable energy technologies. As a representative of renewable energy sources, solar energy gradually shows its advantages of clean and renewable. It is laden with the weighty responsibility of replacing conventional resources [2, 3].

At present, there are two successful technologies in the application of solar energy utilization: solar thermal and photovoltaic (PV). Solar thermal utilization generally includes solar-to-thermal technology by using non-concentrating or concentrating collectors and solar-to-electric technology, which is also called concentrating solar power (CSP) by using concentrating collectors [4-7]. Due to its concentrating and thermal storage properties, solar thermal utilization has been rapidly developed. It is widely recognized as one of the most competitive technologies to meet the increased demands of thermal energy and electricity in the future [8-11]. Although the solar thermal system can convert the full spectrum energy to thermal energy, its efficiency remarkably decreases, and the cost of the system increases when the working temperature increases [12].

By contrast, PV technology generates electricity directly from the sunlight and has been developed to be one of the central renewable energy source generations in the world [13]. Because the photovoltaic effect can only be generated in the part where the energy of solar photons exceeds the bandgap of PV cells, PV technology has strong spectrum selection characteristics [14, 15]. The spectral response wavelength of PV cells exists in the visible light and near-infrared [16]. It can only generate electricity with high efficiency in a specific solar spectral range. The rest of the spectral range was either lost or absorbed by the electrode or the backplate to generate heat. The temperature rise affects the energy bandgap of the PV cell, which can cause cell performance degradation, failure, or deformation. Therefore, passive or active cooling is needed to maintain the temperature of the PV cell to ensure the highest efficiency and service life [17, 18].

Concentrating photovoltaic/thermal (CPV/T) or photovoltaic/thermal (PV/T) hybrid systems were successfully developed to overcome the temperature increase problem and achieve the highest potential for energy harnessing [19, 20]. However, due to the temperature rise harming the performance of PV cells, it is always recommended to keep the operating

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temperature less than 80 °C and 50℃ for CPV cells and PV cells, respectively [21, 22]. Therefore, the thermal energy obtained in the CPV/T or PV/T systems generally is in a lower temperature range and lower quality for solar energy application. To realize the temperature decoupling of photovoltaic and photothermal, various spectral beam splitting (SBS) techniques are used to overcome these problems. SBS can transmit the wavelengths of sunlight that effectively produce electricity to the PV cells, but the unwanted wavelengths of sunlight for PV to the solar receiver for thermal energy. Through the SBS technology, the combination of PV and concentrating solar thermal (CST) in a hybrid system can be achieved to simultaneously generate electricity and high-value thermal energy, which may be used to generate electricity as well [23, 24]. As one of the most innovative and applied value technologies, the hybrid solar converters based on SBS technology were supported to optimally exploit the solar spectrum and reach higher conversion efficiencies by the International Energy Agency and ARPA-E in 2013 [25, 26].

SBS technology separates the sunlight according to the different wavelengths. It efficiently utilizes solar full-spectrum radiation energy and maximizes solar energy utilization [27]. At present, as the most crucial component of this technology, the optical filter for accomplishing spectrum splitting for hybrid PV and photothermal mainly including solid interference filter, liquid absorptive filter, holographic filter, luminescent filter, and spectrally selective solar cells [28-30]. Extensive studies [23, 31-33] focus on developing many PV /CST hybrid systems using spectral splitting filters. The advantages of direct absorption and heat transfer adequately of liquid absorptive filter require further investigation by researchers [34]. The solid interference filters were reviewed on the published research in 2003-2013 [29]. Part of the integrated designs of PV/CSP hybrid systems was summarized in the review by Ju [23, 28].

As an emerging technology, the development of the spectral splitting filter used in PV/CST hybrid systems is high-speed recently and has not been reviewed. The purpose of this paper is to provide an up-to-date review of the recent research of the spectral splitting filters and to evaluate prospects of the SBS technology in PV/CST hybrid systems. We sort out the concepts or technologies about the spectral splitting filters in a hybrid system and summary the compositions, performance advantages, application fields, research trends, and technical obstacles of the filter. We also present extensive application prospects for SBS technology in combined heat and power cogeneration in medium and high temperatures.

2. THE BASIC CONCEPT OF SBS TECHNOLOGY

Jackson [35] first proposed the concept of SBS technology in 1955. The pioneering research has been developed by Moon *et al*. [36] to achieve a high-efficiency photoelectric conversion of solar cells through practical means in 1978 [37]. In past decades, extensive researches have elaborated and applied SBS technology to various photovoltaic and photothermal hybrid utilization systems [38-42].

Solar irradiation can be divided into the ultraviolet (<380 nm), visible (in the wavelength range from 380-760 nm), and near-infrared (in the wavelength range from 760-2500 nm). The solar spectrum (300-2500 nm) region accounts for about 99% of the total solar energy and is the target range for solar energy utilization, as illustrated in Figure **1**.

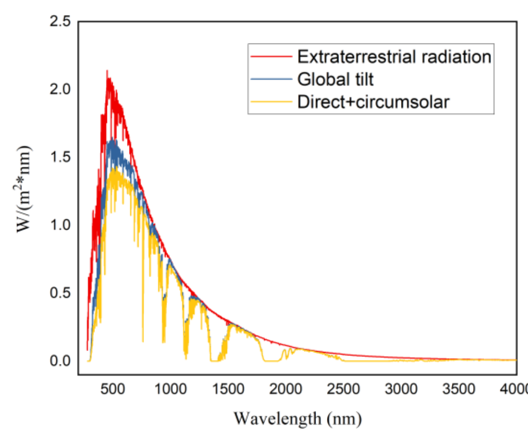


Figure 1: Extraterrestrial (red), global (blue), and direct (yellow) solar spectra.

The SBS technology uses special optical filters to re-separate the spectrum for energy distribution and utilization [43]. Utilized by the reflection, transmission, and absorption of the filters, this technology sets up spectral splitting filters on the light source's side. It separates the spectrum of the higher wavelength band to the PV cell for photoelectric conversion and separates the spectrum of the remaining wavelength bands' energy to other receivers. The concept of SBS technology was proposed to achieve the efficient conversion of PV cells [44]. If the "ineffective and redundant" spectrum of PV cells is used efficiently, it realizes the full-spectrum utilization of solar energy utilization.

From the perspective of energy conservation, when the sunlight reaches the surface of spectral splitting filters, the solar energy will be divided into three parts: reflected, transmitted, and absorbed. The relation of these three parts can be written as

$$\alpha + \tau + \rho = 1 \tag{1}$$

where $\alpha(\lambda)$, $\rho(\lambda)$ and $\tau(\lambda)$ represents the absorptance, reflectance, and transmittance, respectively. The ideal spectral splitting filters should satisfy low absorption, high reflection, or high transmission optical characteristics.

According to the optical filters and principal structure, the spectral splitting filters are described in detail, including solid interference filters, liquid absorptive filters, holographic filters, luminescent filters, and PV filters, as shown in Figure **2**.

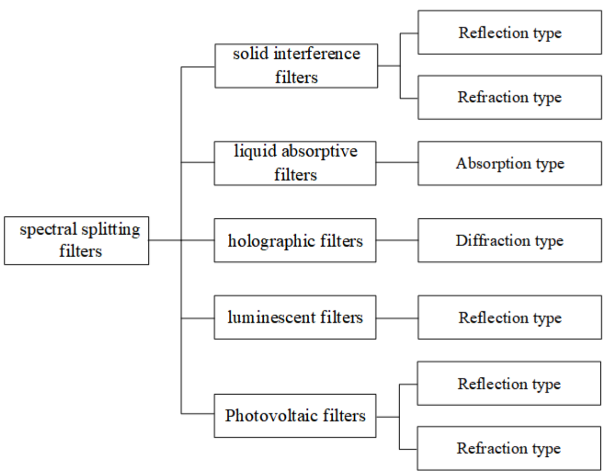


Figure 2: Classification of the spectral splitting filters.

2.1. Solid Interference Filters

The solid interference filters, also called dichroic filters [33, 45-47], were periodically arranged using materials with different refractive indices. The principle was the mutual interference of different materials on the spectrum. By optimizing the thickness and the number of materials, the spectral splitting filter has a high sunlight transmittance in a specific wavelength. The optical performance in the whole wavelength presents a step-like waveform function. It has a remarkable spectral splitting effect, stable working performance, mature processing technology, and without any absorption. However, the spectral splitting filter requires a substrate whose shape was limited. The spectral splitting filter cannot eliminate the sideband loss. Simultaneously, it has a strong dependence on the incident angle of sunlight. As shown in Figure **3**, according to the design structure of the solid interference filter, the material, and the application, the filter is classified into seven types: the Rugate filter, the multilayer bandstop filter, all-dielectric multilayer filter, metal-dielectric multilayer filter, and other filters.

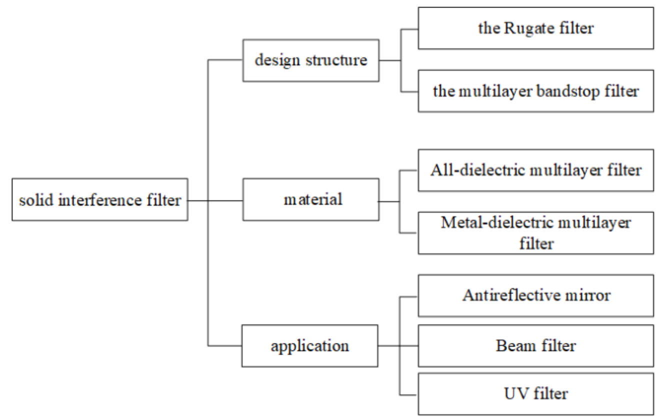


Figure 3: Classification of the solid interference filters.

2.2. Liquid Absorptive Filters

By using the spectral selective absorption liquid as a spectral splitting filter, the liquid absorptive filter achieves strong absorption of the spectrum in a particular wavelength and high transmission characteristic for the other wavelength [48, 49]. The filter uses the liquid's unique optical characteristics to directly absorb and convert the solar energy into heat energy in the inefficient photoelectric conversion wavelength [24, 50]. The rest of the solar energy reaches the PV cell's surface through the liquid absorptive filter. The liquid absorptive filter has several benefits, such as separateing spectral, absorbing the solar energy, converting it into heat energy, storing and transporting heat energy, and avoiding heat loss due to secondary heat exchange. This fluid can be used as a heat transfer fluid to cool PV cells, essentially solving the temperature rise problem of PV cells. Moreover, the liquid splitting filter can minimize the fluorescence phenomenon when controlling the battery heating. Compared with the solid splitting filter, the liquid splitting filter's high-effective splitting characteristic is more comfortable to realize [51, 52].

By changing the liquid type, concentration ratio, and liquid film thickness, the filter can achieve different spectral splitting effects [53]. Generally, the filter of traditional liquid, including water, inorganic matter, organic matter, and some salt solutions, cannot match the spectral response of PV cells in PV and photothermal hybrid systems, which reduces the overall conversion efficiency of the system [54, 55]. For this reason, many researchers have turned their attention to nanofluids, including water-based, magnetic electrolytes, etc. [56-58]. For forming the nanofluid, nanostructured particles are suspended in the base fluid. The surface morphology of the nano-structure provides a substantial heat transfer capability [59]. Since the diversity of nanofluids, the filter of nanofluids has become the focus of liquid absorptive filters. However, the nanofluid as a splitting filter also has certain deficiencies, such as stability in high-temperature, environmental hazards, and synthesis costs [60].

2.3. Holographic Filters

The construction of the holographic spectral splitting technology was the homogeneous Bragg-Lippmann reflection hologram theory. The holographic mirror reflected or transmitted the solar radiation of different wavelengths, which focused at different positions. According to each focus's solar wavelength, different PV cells were matched, which improves the spectrum's overall utilization [61, 62]. The advantages of holographic spectral splitting technology include concentrating and splitting solar energy, utilizing diffusing radiation without employing tracking systems [63]. Although a single holographic optical element has low cost, narrow spectral splitting wavelength, and low splitting efficiency. However, the system generally requires a large-area arrangement of holographic optical elements, which has a complicated design and high cost. Therefore, the lack of practical holographic spectral splitting filters with high spectral splitting efficiency and comprehensive wavelength utilization.

2.4. Luminescent Filters

In PV cells, the luminescent spectral splitting filter was converting part of the solar energy into fluorescence or phosphorescence at the edge of the light-emitting panel. The long-wavelength spectrum radiation was converted into heat energy on the heat receiver through the flat plate, collecting direct and diffuse radiation. Although the luminescent spectral splitting filter is applied in hybrid systems without experience tracking systems, its efficiency is still very low [64]. Therefore, this kind of filter is not widely utilized in hybrid systems.

2.5. Photovoltaic Filters

The PV cell can directly be utilized as a spectral splitting filter [23]. By using the optical properties of semiconductors, transparent PV cells can achieve SBS functions [65]. When photons with energy lower than the energy bandgap, the sunlight can pass through the PV cell. The sunlight will be absorbed by the PV cell due to the energy close to or higher than the energy bandgap. However, the process mentioned above is ideal. Transparent PV cells cannot fully absorb sunlight in the wavelength range from 400-1100nm and have a low transmittance at the 1100-2500nm region. Therefore, it is difficult to manufacture the high-transmittance PV cells in PV/CST hybrid system.

3. DEVELOPMENTS OF THE SPECTRAL SPLITTING FILTERS

According to the different classifications of spectral splitting filters, their applications in photovoltaic and photothermal hybrid systems are quite different. Based on the type of spectral splitting filter, the researchers proposed the following spectral splitting filter method [32], as shown in Figure **4**. Figure **4(a)** shows a schematic diagram of the selective reflection spectral splitting filter. The selective reflection spectral splitting filter divides the incident light into two parts. Part of the spectrum was reflected in the PV cell, and the remaining part of the spectrum was transmitted to other energy converters. The optical diffraction concept can also be combined with a spectral splitting filter, as shown in Figure **4(b).** The optical diffraction device separates the spectra with different wavelength bands and allocates them as needed. Spectral splitting filter based on refractive index device, as shown in Figure **4(c)**. The idea was similar to that of optical diffraction. The spectrum can be divided into several parts according to the refractive index of different wavelength bands. The selective absorption spectral splitting filter is shown in Figure **4(d)**. The spectral splitting filter selectively absorbs part of the band spectrum for other energy conversions, and the other bands are transmitted to the PV cell for photoelectric conversion. Under the premise of meeting temperature and efficiency, the system's overall structure and cost need to be considered. As mentioned above, it is necessary to categorize SBS technologies according to various sunlight changes in PV/CST hybrid systems, as illustrated in Figure **4**.

Combining the spectral splitting filter classification and the filter structure, the solid thin-film spectral splitting filter, the holographic spectral splitting filter, and the luminescent spectral splitting filter are applied in the photovoltaic and photothermal hybrid system based on the spectral splitting method of selective

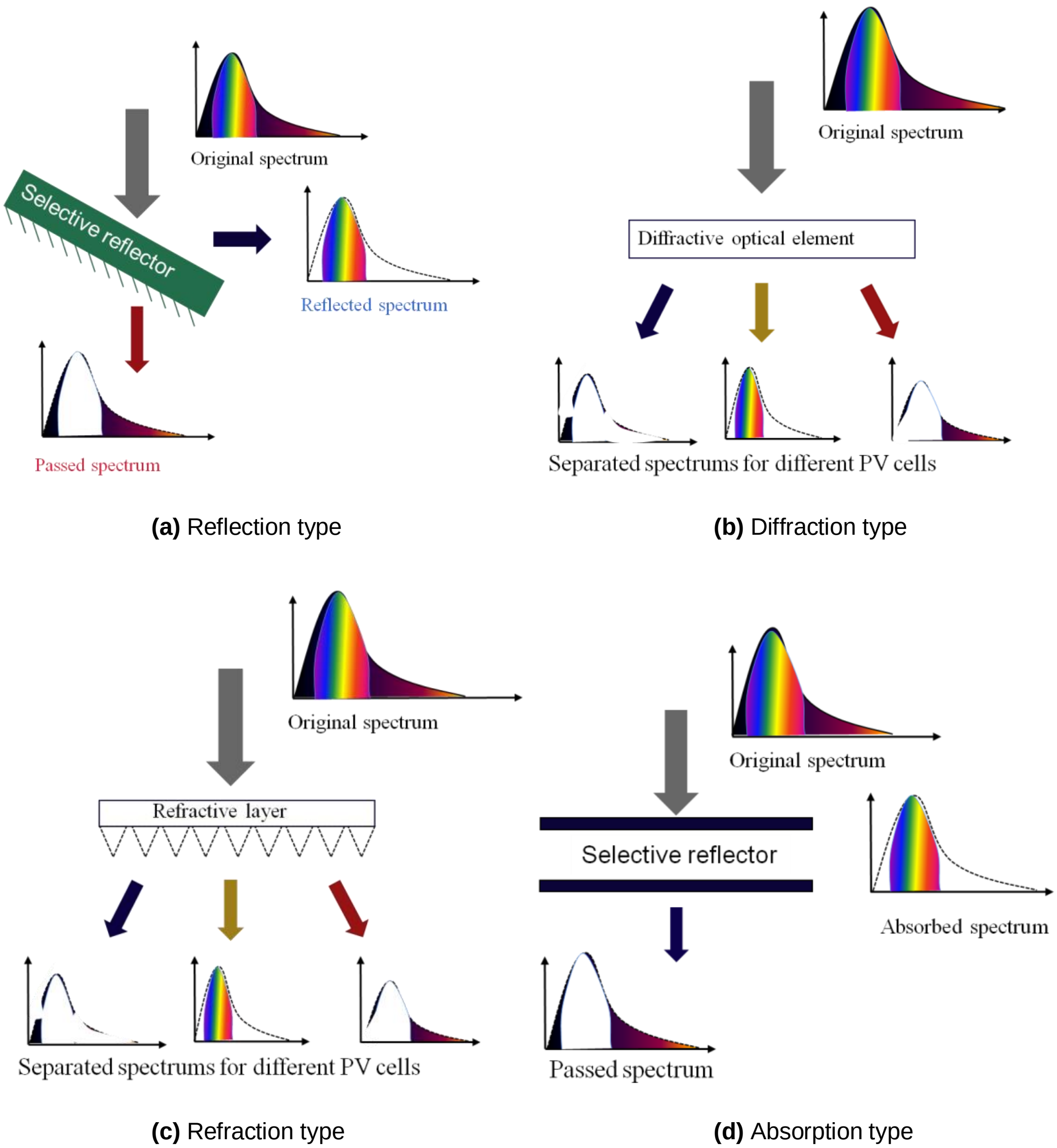


Figure 4: Schematic diagram of the spectral splitting filters [32].

reflection. Most liquid spectral splitting filters are selective absorption spectral splitting methods widely used in PV and photothermal hybrid systems [66]. Spectral selective splitting filters can be used in various photovoltaic and other energy conversion processes to achieve the synergy of various energy fields and maintain a high solar energy full spectrum effective energy conversion [44].

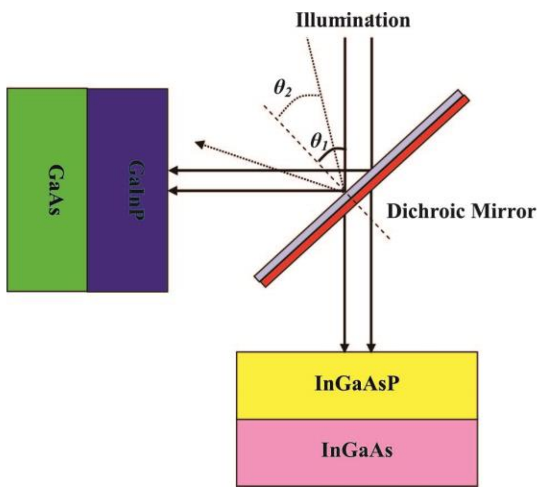
At present, most of the research on the development of SBS technology based on diffraction and refraction has mainly focused on high-efficiency power generation using different PV cells. Less effort has been made on diffraction and refraction-based filters applied to photovoltaic and photothermal collectors. A key reason for this preference was the concern about the high cost and reliability of these filters in practical applications. However, with further research and development, it is expected that filters based on diffraction and refraction might find potential applications in PV/CST hybrid systems, especially they have excellent concentrating properties in addition to SBS. The system based on diffraction and refraction does not require an additional optical concentrator, resulting in lower cost and more straightforward system configuration [32].

Therefore, in this section, we will conduct an extensive research review according to the primary classification of spectral splitting filters and the order of SBS methods in Section 2.

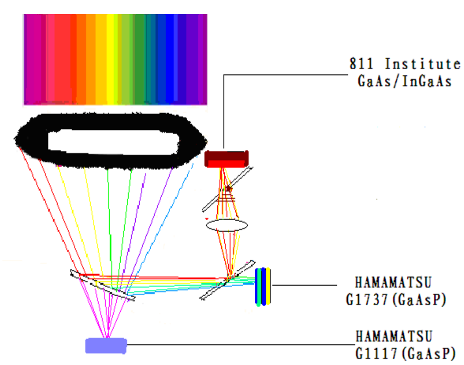
3.1. Solid Interference Filters

The dichroic mirror is relatively simple in terms of the theoretical concept and comprehensive design [67]. Mojiri *et al*. [68] sorted out the research content of the dichroic mirrors as spectral splitting filters before 2013. To the high-response wavelength of the PV cell was reflected on the cell surface, the sunlight was spectrally divided by the dichroic mirror. Hence, it was necessary to split the spectrum to match the required PV cells to obtain a very high solar conversion efficiency. By utilizing a dichroic mirror, the lattice-matched GaInP/ GaAs, and InGaAsP/InGaAs double-junction cells, Xiong *et al*. [69] achieved the SBS of the four-junction system, and the system efficiency was 29.2%, as shown in Figure 5**(a)**. Zhao [70] spitted the spectrum into three bands, which increased the system efficiency to 38%, as shown in Figure **5(b)**. Using two dichroic mirrors to realize the concentrating and splitting of AlGaAs, GaAs, and GaSb PV cells, the overall efficiency of the system reached 39.6 % [71], as shown in Figure **5(c)**. When the PV cell has a perfect diode structure, the spectrum can be spitted into five bands, which reached an ideal efficiency of 42.7% [72], as shown in Figure **5(d)**. Furthermore, Mitchell [73] applied a two-stage spectrum splitting strategy integrating three solar cells, including $Ga_{0.51}In_{0.49}P$, Si, and GaSb. For achieving ultra-high total photoelectric efficiency (>50%), Eisler *et al*. [74] utilized a polyhedral specular reflection as a spectral splitting filter, which applies multi-stage spectral splitting to seven different solar cells. However, the addition of the dichroic mirror increases the loss of SBS, and the shortwave receiver was a more sensitive result from the daily and seasonal changes of the spectrum.

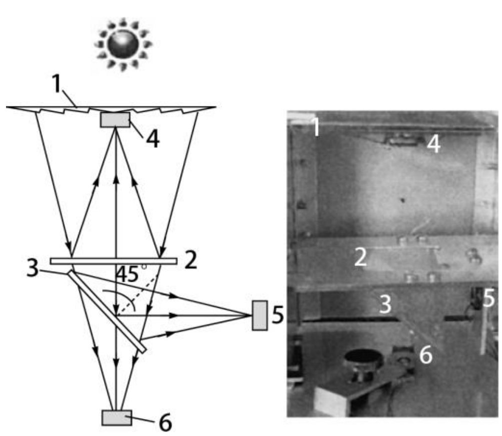
Jiang *et al*. [75] used Nb_2O_5 / SiO_2 coating as SBS and applied it to the second parabolic trough concentrating photovoltaic and photothermal hybrid systems. As shown in Figure **6(a)**, the overall theoretical optical



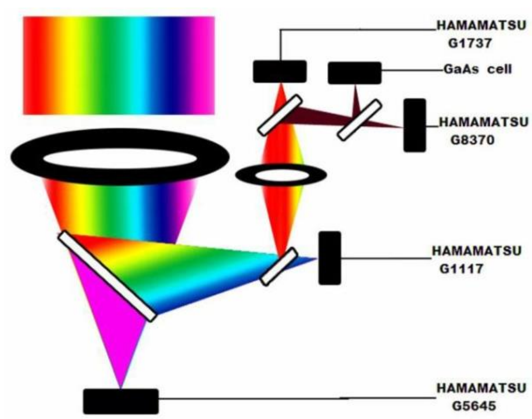
(a) A dichroic mirror [69]



(b) Three dichroic mirrors [70]

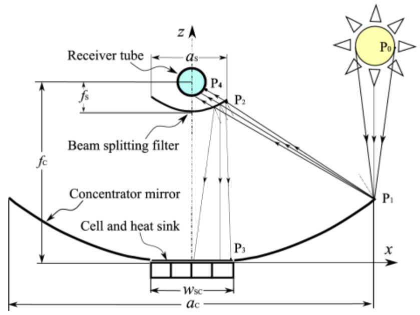


(c) Two dichroic mirrors [71]

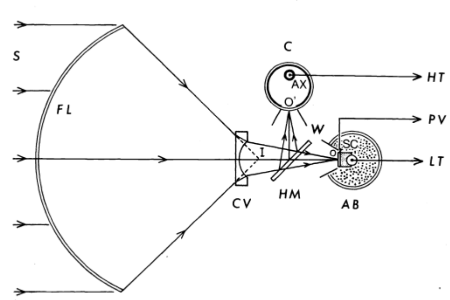


(d) Four dichroic mirrors [72]

Figure 5: Schematic diagram of SBS of the dichroic mirror.

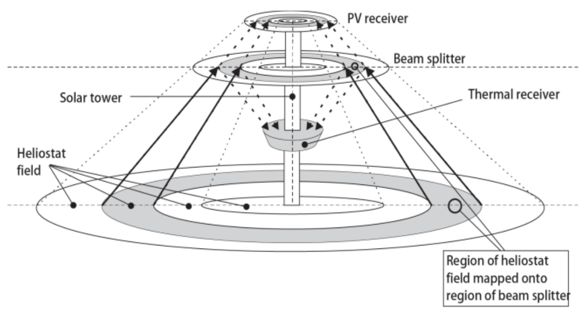


(a) second parabolic trough [75]

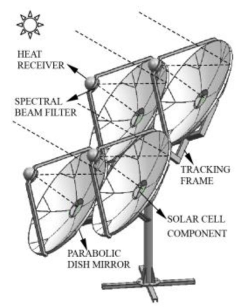


(b) secondary linear Fresnel lens [76]

Figure 6: SBS system based on the solid film.



(a) SiO_2 and TiO_2 materials [77]



(b) Nb_2O_5 and SiO_2 materials [78]

Figure 7: Schematic diagram of the hybrid system.

efficiency of the system was 76.4%, and the thermal load of silicon cells decreased by 20.7 %. The other hybrid system has a linear Fresnel lens concentrator as the secondary concentrator [76]. As shown in Figure **6(b)**, the reflection filter of the interference dielectric multilayer with a transmittance of 96% was added, which reached the system efficiency of 69.2%. The above two devices are still in the theoretical calculation stage, without an experimental platform was built.

Imenes *et al*. [77] utilized SiO_2 and TiO_2 materials to make a radial spectral splitting filter, which can be optimized according to the largest proportion of incident energy to maximize the annual energy conversion efficiency of the system, as shown in Figure 7**(a)**. Jiang *et al*. [78] designed and manufactured a 38-layer Nb_2O_5 and SiO_2 spectral splitting filter. Based on a three-dimensional optical model, the two-stage dish concentrating photovoltaic and photothermal system with the spectral splitting filter had an optical efficiency of 78% and the power generation efficiency of 18 %, the specific structure of the system as shown in Figure **7(b)**. The two kinds above spectral splitting filters had a high cost, and the concentrating cells needed the cooling device.

For reflecting the infrared band to the collector tube, Tejas [79] proposed to coat a selective transmission film composed of multiple layers of transparent dielectric materials on the CPC's surface. The sunlight was transmitted to the underlying thin-film CdTe PV cell. Due to its total energy conversion efficiency was only 20%, the design can be applied to the roof, as shown in Figure 8.

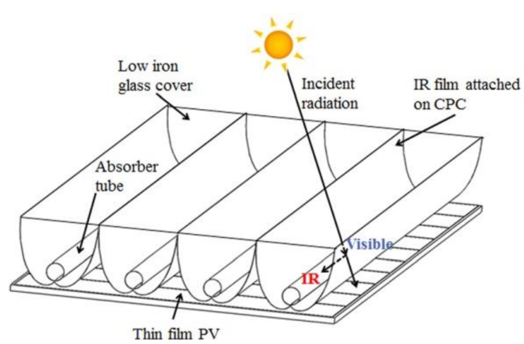


Figure 8: CPC-based hybrid system by Tejas [79].

Kate's team [80-82] studied a kind of "PV mirror" to replace the silver groove to achieve the purpose of concentrating light on the photothermal unit. The PV mirror acts as a concentrator, a spectral splitting filter,

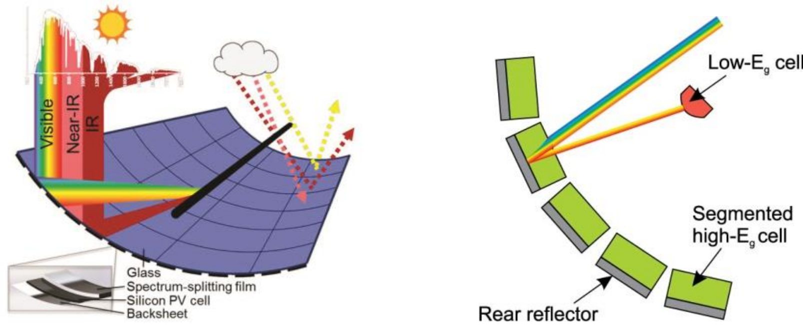


Figure 9: Schematic diagram of PV mirror [80, 81].

and a high-efficiency photoelectric converter. The PV mirror was made of organic material, which transmitted near-infrared light to the bottom silicon PV cell, then reflected other wavelengths to the thermal absorption tube, as shown in Figure **9**. However, the PV cell was bent to a certain extent to match the shape of the trough, which increased the processing cost of the PV cell. Hence, the author conducted a segmented experiment on the parabola "PV mirror" in the later stage. The addition of filters has increased the system's cost by 10%, but the hybrid system has increased its annual energy output by 53%.

Liang [83] designed and established a hybrid system based on the SiO_2/TiO_2 interference film. The hybrid system exhibited excellent overall optical properties, including a reflectivity of 96.8% and the transmittance of 85% of the filter, which achieved maximizing solar energy use. The filter reduces the operating temperature of PV cells by 3K, which improves the system's overall efficiency and exergy efficiency. The schematic diagram of the structure, as shown in Figure **10**.

Wang [84] fabricated a 58-layer spectral splitting film based on Ge and SiO_2, which as high and low refractive index coatings, as shown in Figure **11**. The overall reflectance and transmittance of the filter are 30.6% and 69.4%, respectively. The spectral splitting film, including high transmittance (89.6%) with the PV cell response bands, and high reflectance (98%) with the photothermal unit, and good optical performance, was designed. The author [85] used Nb_2O_3 and Na_3AlF_6 as high-refractive-index materials and Ge as low-refractive-index materials to make a 13-layer spectral splitting film. When the filter of average transmittance of 72.1 % and the reflectivity of 27.9 % was applied to a hybrid system, the overall optical efficiency of the system was 76.3% during the sun tracking error was less than 1. Comparing the same conditions, the photovoltaic conversion efficiency and overall energy efficiency of the above hybrid systems are higher than the single photovoltaic system [86].

Sibin *et al*. [87] prepared the ITO/Ag/ITO multilayer coatings by a magnetron sputtering method, and the coatings were designed for spectral beam splitter applications. Due to the nano-porous microstructure formed on the glass substrate surface, the filter had high visible transmittance of 88% and high near-infrared and infrared reflectance above 90%, an optimum cut-off wavelength of900 nm. Figure **12** shows

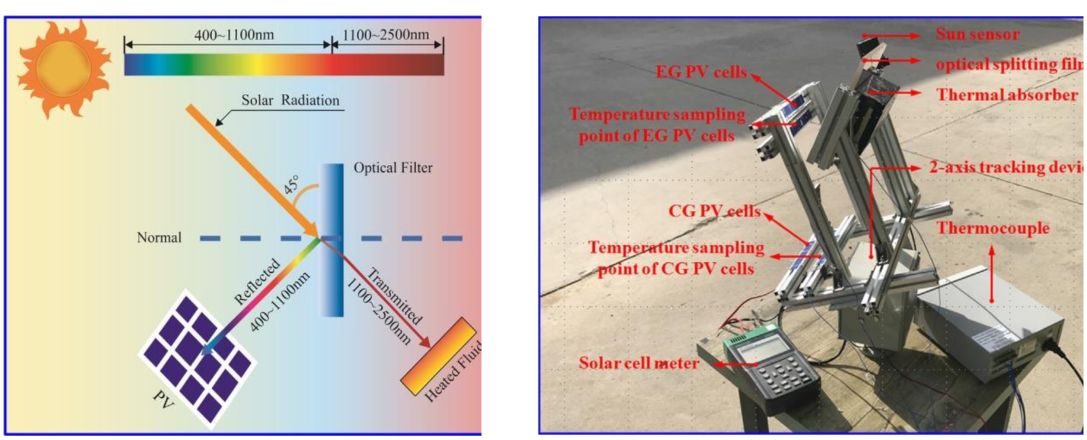
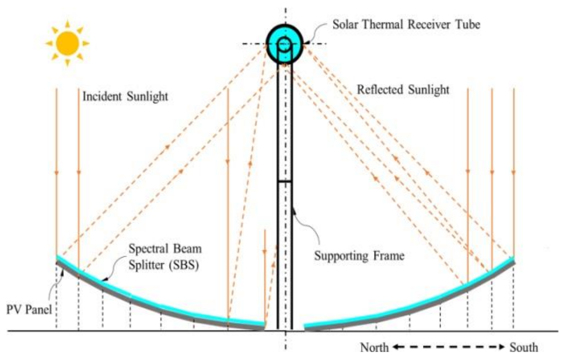
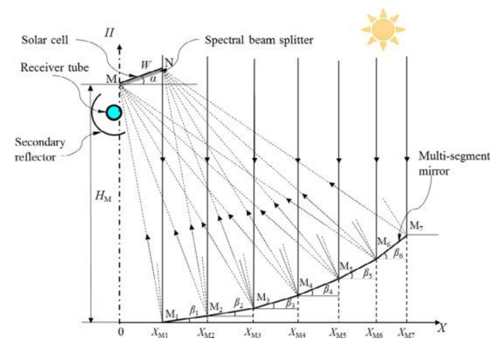


Figure 10: Hybrid system diagram based on the spectral splitting film [83].

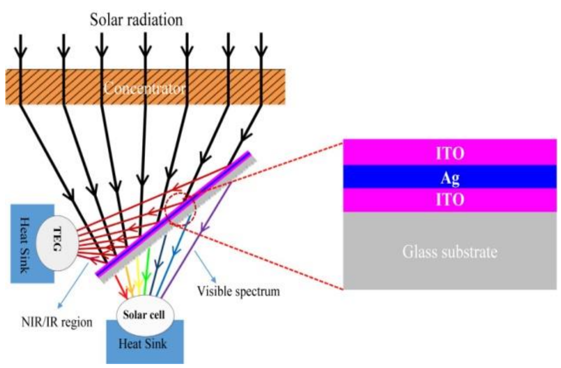


(a) 58-layer spectral splitting filter [84]

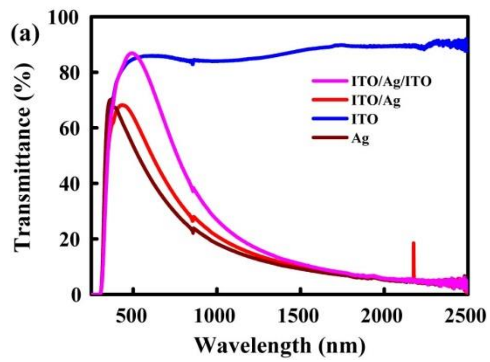


(b) a 13-layer spectral splitting film [85]

Figure 11: Hybrid system diagram based on the spectral splitting film.

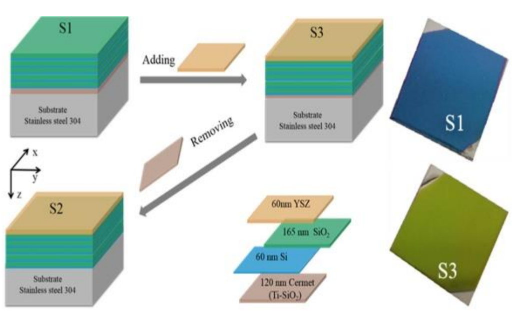


(a) Schematic diagram

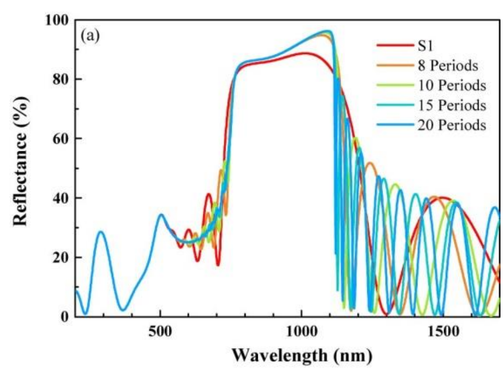


(b) Transmittance spectra

Figure 12: Diagram of ITO/Ag/ITO multilayer system [87].



(a) Schematic diagram



(b) Reflectance spectra

Figure 13: Diagram of solar spectral optical filter [88].

the schematic diagram of the filter and the transmittance spectra.

Dong [88] designed the spectral beam splitter, including a cermet layer, Si/SiO_2 1D photonic crystal, and top heterostructure layer by the magnetron sputtering method. Due to the mismatching of impedance between free space and the heterostructure structure, the reflectance of the filter increased in a range of the photovoltaic band, which can be arrived at higher than 92%. Figure **13** shows the schematic diagram of the filter and the reflectance spectra.

3.2. Liquid Absorptive Filters

Different from the solid spectral splitting filter, the liquid absorptive filter is made into a heat receiver based on the selective absorption SBS method, which absorbs the solar energy that cannot be effectively used by the PV cell in the photoelectric convert process and directly converts this energy into heat [89]. Due to the requirements of the different liquids in solar application systems, including heat transfer, optical adaptation, SBS, or a combination of the above applications, different fluid characteristics are required. Vicar *et al*. [31] analyzed the primary physical, optical, chemical, and thermal performance requirements of various liquids. The summarized four primary liquids with different chemical structures on the market: synthetic oil, silicone oil, glycol, and mineral oil. Zhao *et al*. [90] obtained the filter's optical parameters through the inverse method based on the hybrid system's genetic algorithm. The solar radiation of 200-800nm, 84% of the visible light, was transmitted to the solar cell for photoelectric conversion. In the infrared part of the spectrum from 800-2000nm, 89% of the infrared radiation underwent a photothermal conversion. The working fluid absorbs about 92% of solar infrared radiation and transmits 89% visible light.

Mojiri *et al*. [29] proposed combining a dichroic filter with a direct absorbing liquid to achieve spectral splitting. As shown in Figure **14**, a dichroic filter was installed in front of the silicon solar cell, and the sunlight sheet reflects the radiation below 700nm was absorbed by the dichroic filter on the side. The working liquid flowed between the front glass cover and the dichroic filter, directly absorbing wavelengths above 1100nm. The filter was made of TiO_2 and SiO_2 as high and low refractive index materials, which had a transmittance of 92.6% and the low transmittance of about 12.5% within a range of beyond 1125nm. The transmittance was determined by the intrinsic absorption coefficient of the liquid and its thickness.

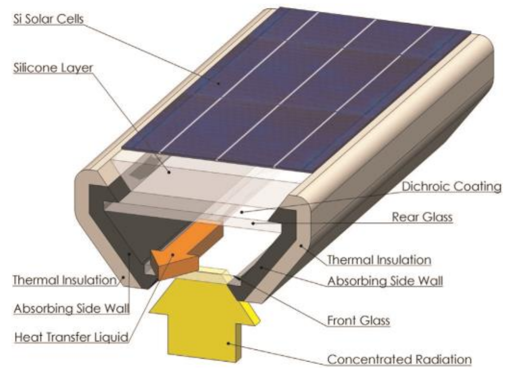


Figure 14: System diagram of the dichroic filter and absorbing liquid spectral splitting filter [29].

An [91] made a kind of organic polymer nanofluid by studying non-toxic and non-corrosive polypyrene and applied it in the concentrated hybrid system, as shown in Figure **15**. The fluid had a relatively low transmittance when the wavelength is less than 300nm and greater than 800nm, but the transmittance is relatively high at 300-700nm. By changing the fluid concentration, the hybrid system's performance can be affected, and the transmittance can best reach 83.2%. Simultaneously, the author studied the spectral splitting effect of the oleyl amine fluid of Cu9s5 nano-particles under the same experimental device [92]. The spectral splitting fluid had a high absorptance at 800~1600nm and transmittance at 400-800nm.

Han *et al*. [93, 94] combined Ag/$CoSO_4$-propylene glycol nanofluid to make a spectral splitting filter, which applied it in a concentrated photovoltaic/thermal system. The schematic structure is shown in Figure **16**. By discussing the influence of the concentration ratio,

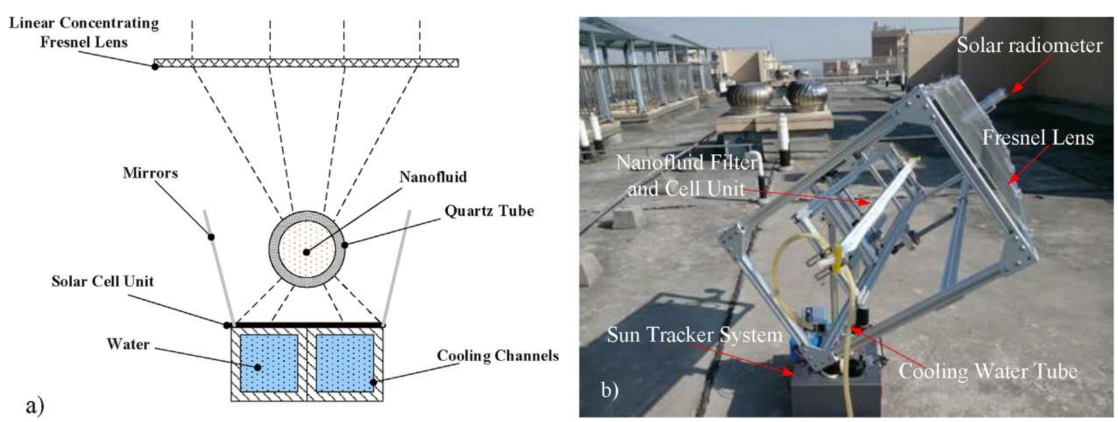


Figure 15: Schematic diagram of the absorbent liquid frequency division system [91].

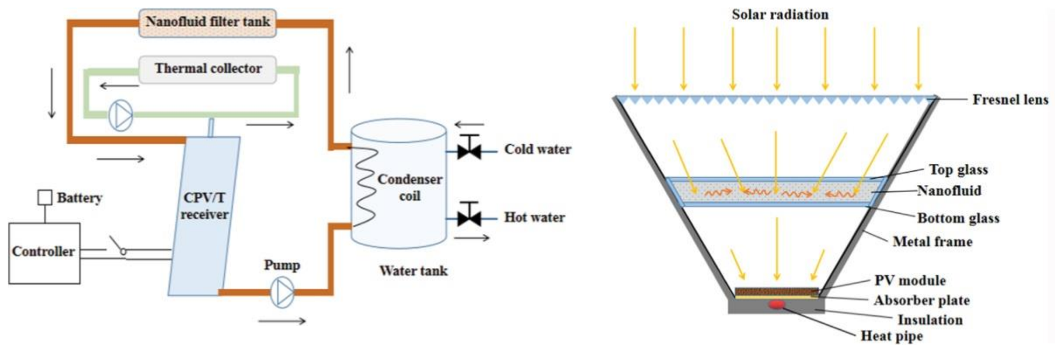
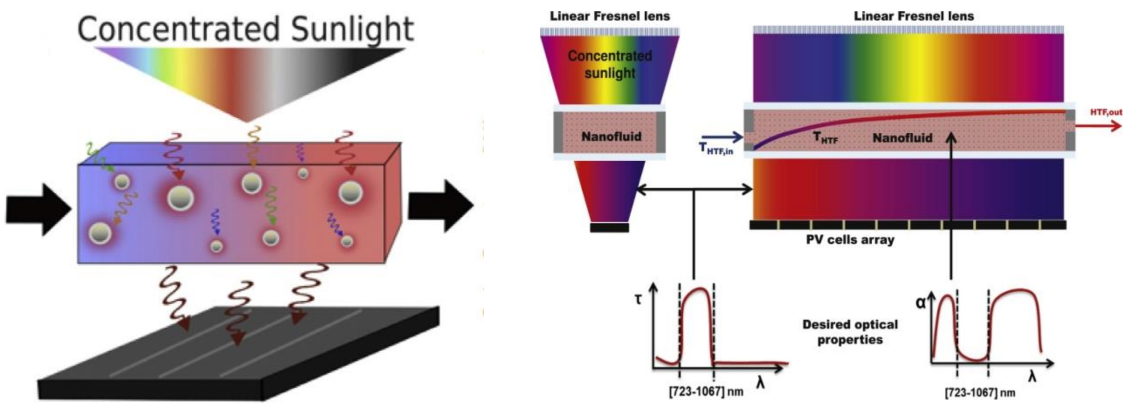


Figure 16: Schematic diagram of CPV/T system based on nanofluid [93, 94].



(a) Hjerrild *et al*. [95] **(b)** Crisostomo *et al*. [96]

Figure 17: Schematic diagram of the hybrid system based on Ag-SiO_2.

the liquid's mass flow rate, the quality in the water tank and the collector, the ambient temperature, and the overall system's wind speed, we can draw the following conclusions when the quality fraction of Ag nano-particle was 37ppm, the evaluation function of the hybrid system reached the maximum value. Moreover, the absorptance (70.87%) of the Ag/$CoSO_4$ nanofluid in the ultraviolet and visible wavelengths region was higher than water-based fluid at the same quality fraction of silver nano-particles. However, the experiments and data on the stability of nanofluid spectral splitting filters under high-temperature from outdoor were absent.

Hjerrild *et al*. [95] studied the stability of the glycerol-based fluid with core-shell silver-silica nano-particle suspended to form a liquid optical filter, as shown in Figure **17(a)**. By changing the silicon coating process of Ag-SiO_2 nano-particles, the stability of the filter was improved at high temperatures. The filter had high transmittance in the wavelength range of 725-1100nm, and its cost was $3/l. Crisostomo *et al*. [96] also utilized Ag-SiO_2 nano-particles to make a liquid spectral splitting filter, achieving high transmittance in the 723-1100nm region, as shown in Figure **17(b)**.

Walshe *et al*. [97] developed a series of liquid spectral splitting filters with luminous imidazole-phenanthroline groups dispersed in ethylene glycol, which were used in the hybrid system of monocrystalline silicon cells, as shown in Figure **18**. The filter with organic metal had a high transmittance of about 95%-98% in the range of 250-1000nm, and the maximum concentration of each compound was 0.5wt%. By increasing the added compounds' concentration, the system's overall efficiency will be further improved, but many factors limit the concentration.

Huang *et al*. [98] completed a silica-coated silver (Ag) nano-particle that uses dimethylamine (DMA) as the primary solvent to induce the hydrolysis of tetraethyl orthosilicate (TeOs). Subsequently, suspending Ag@SiO_2 nano-particle with controllable silicon shell thickness in propylene glycol-$CoSO_4$ hybrid fluid, the liquid spectral splitting filter of plasma nanofluid was made. The system structure is shown in Figure **19**.

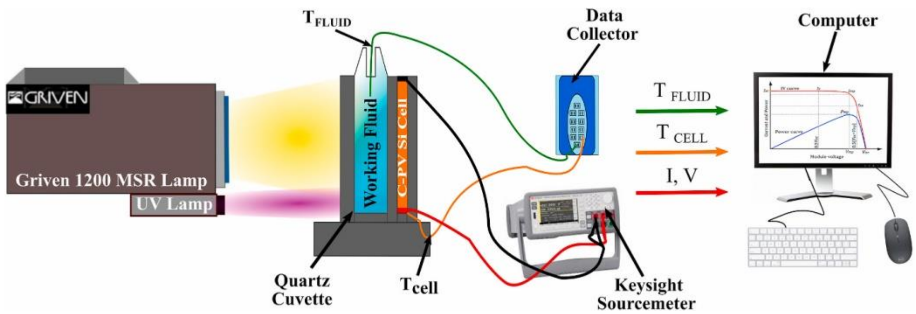


Figure 18: Schematic diagram of the hybrid system based on organometallic [97].

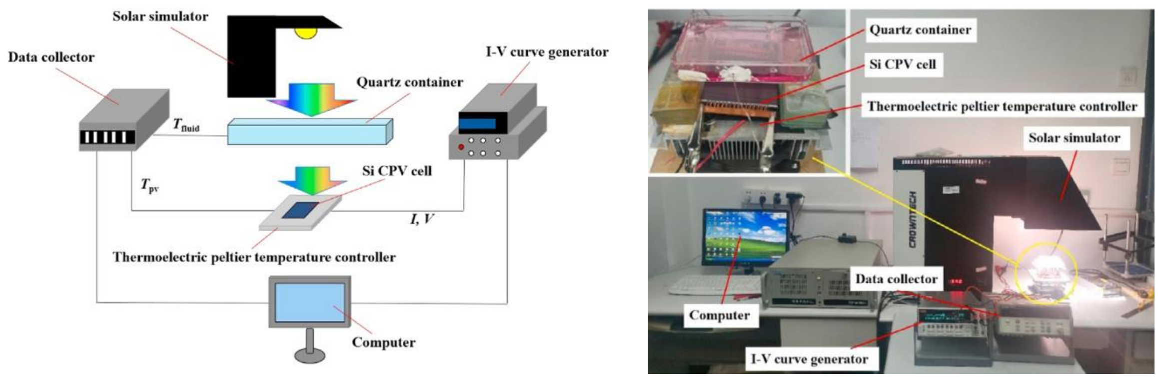


Figure 19: Diagram of a plasma-based spectral splitting filter [98].

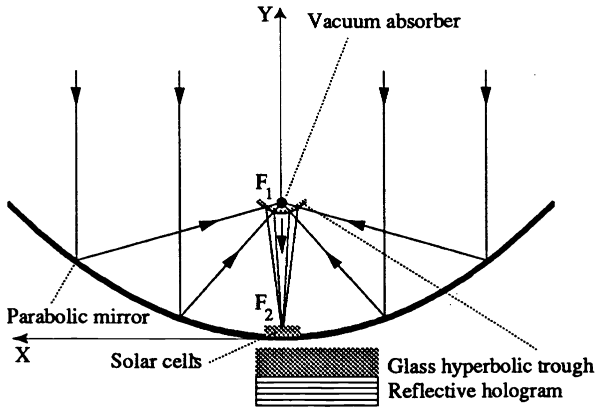
When the thickness of the silicon shell nano-particle in this system was 34nm, and the absorption peak of 474nm, the filter was close to the maximum point of the spectrum. The spectral splitting efficiency reached 39.3% at the concentration of Ag@SiO_2 nano-particle is 25.4mg/l, which had better spectral matching with silicon PV Cells comparable to neat propylene glycol filters. However, the response band's transmissivity with the PV cell is tapered, and the overall transmissivity is low.

3.3. Holographic Filters and Luminescent Filters

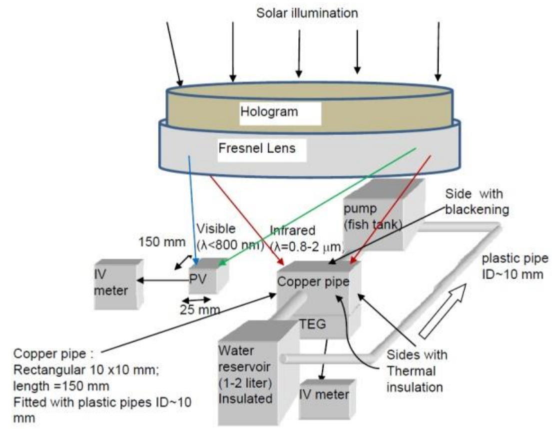
Due to the efficiency of processing and designing systems, holographic and luminescent optical spectral splitting filters are rarely used to design photovoltaic and photothermal hybrid systems. In the following content, we select representative examples to explain.

The holographic layer can be designed to diffract a specific wavelength and diffract sunlight to the desired direction. Therefore, the holographic SBS technology can provide various improved methods for existing solar energy conversion devices and systems [62]. Kostuk *et al*. [99] diffracted the long-wavelengths in the spectrum to the right and the short-wavelengths to the left based on the geometric and diffraction efficiency characteristics of the holographic optical element, which achieved the purpose of SBS. Sunlight was utterly reflected by the holographic layer, reaching the PV cells to collect the diffraction spectrum's energy. During the development of holographic optical elements, large-scale manufacturing of holographic optical elements at 300-500nm is impossible due to the expansion of the holographic layer and the shortage of laser lines. Stojanoff *et al*. [100] affixed the holographic layer on the hyperboloid as a spectral splitting filter whose transmission characteristics matched the spectral response of PV in the aperture shown in Figure **20(a)**. Simultaneously, the author adjusted the selectivity, bandwidth, and center wavelength of the incident angle to achieve the design goals. The same concept of diffractive aperture, Vorndran *et al*. [101, 102] also demonstrated that the holographic SBS method could be applied to the hybrid system.

Xia *et al*. [103] used holographic concentrators in heat and power cogeneration. The concentrator consisted of a double-film broadband holographic optical element (HOE) device utilized for energy conversion. The first holographic layer collected the visible part of the spectrum through a photovoltaic unit. Then, the second holographic layer collects infrared radiation for photothermal conversion, as shown in Figure **20(b)**.



(a) PV/CSP



(b) PV/T system

Figure 20: Schematic diagram of holographic frequency division PV/T system [100, 103].

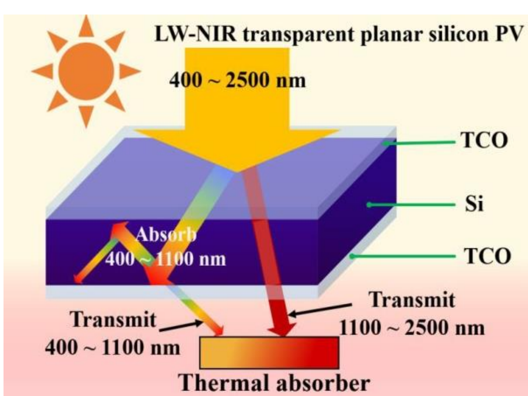
Through measurement showed that the holographic concentrator had a diffraction efficiency of 70-96% for visible light.

The luminescent filter also used the internal reflection of the filter and without the tracking device [104]. For absorbing sunlight at shorter wavelengths and re-emitting photons at longer wavelengths, Kostuk [105] proposed a shifting luminous spectral splitting filter doped with luminous dyes or quantum dot mixtures on a transparent flat. The filter used the total internal reflected sunlight, made fair use of the shorter wavelengths in the spectrum, and reduced the PV cell area. However, the technology did not effectively use longer wavelengths. It also required high costs to degrade on spectral splitting filter substrates of organic dyes and quantum dots doping [106].

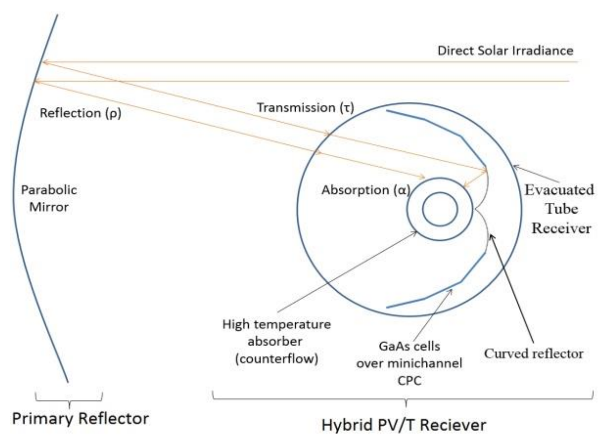
3.4. Photovoltaic Filters

Ellmer [107] developed a transparent conductive oxide (TCO) through indium tin oxide (ITO) and aluminum-doped zinc oxide (AZO). The spectral splitting filter was formed with three components: the oxide, the PV cell, and the anti-reflective coating (ARC) on the cell surface. By the TCO, the wavelength region from 1100 to 2500 nm can pass through the PV cell. The effect of ARC is related to wavelength range, as shown in Figure **21(a)**. Therefore, by optimizing the material, the photovoltaic filters can have a high absorptance of 400-1100 nm and high transmittance of 1100-2500 nm [108].

Winston *et al*. [109, 110] designed GaAs cells on the surface of the CPC, as shown in Figure **21(b)**. The sunlight was divided into three parts by a parabolic



(a) silicon PV cell filter [108]



(b) GaAs cell filter [109]

Figure 21: Schematic diagram of PV cell filter.

mirror, including directly collecting, was reflected in the collector tube, and was converted by the PV cell. When the concentration multiples of the CPC and the heat collection tube are 44.9 and 59.6, the tube temperature was about 400°C, and the system efficiency can reach 48%. However, the photothermal unit's heat loss will increase when the vacuum environment inside the heat collecting tube is destroyed.

With a high transmittance of infrared (IR) of photovoltaic modules, Ji *et al*. [111] obtained a high efficiency and low-cost solar energy conversion system. When photons with energy lower than the energy band gap, the cell's transmittance of 80.1%. The sunlight of 52.7% will be absorbed by the PV cell due to the energy close to or higher than the energy bandgap. The modules had five key components, including a transparent superstrate, encapsulant, PV cells, and optical adhesive, as shown in Figure **22**.

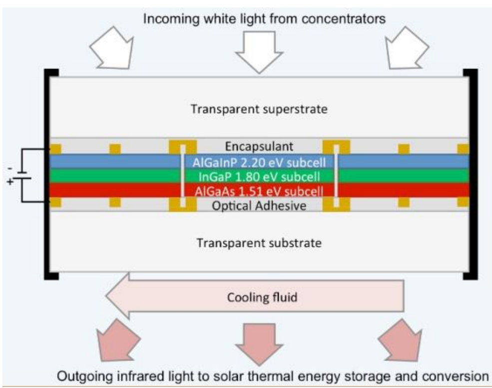


Figure 22: Schematic diagram of transmissive CPV module [111].

4. CURRENT STATUS OF THE SPECTRAL SPLITTING FILTERS RESEARCH

In this part, the research status of the optical SBS technology is systematically and comprehensively introduced, including the development history, potential applications, and research focus of optical SBS. Table **1** summarizes the details of the optical spectral splitting filters described in this article, including an overview of the paper, the method proposed the types and the materials of optical SBS technology. After the analysis in Table **1**, we hope that the information provided in this article can provide more valuable references for researchers to explore the research and application of SBS. Furthermore, the spectral splitting filters can be used in more situations [112-114] and improve energy efficiency [115, 116].

Through VOSviewer software, using citation information, title, and abstract modules to track the literature of SBS technology, we visualize the analysis based on publications from 1981 to January 2021, as shown in Figure **23**. As can be seen from the figure, this content can be divided into the following three parts: energy conversion process, spectrum analysis, and system performance analysis, in which each circle represents a term or keyword, and the size of each keyword is measured by publication the utilization of the keywords. Simultaneously, the distance between two different keywords indicates the number of references they refer to together [117]. That is, the smaller the distance, the higher the number of times that they appear together. The figure shows that SBS

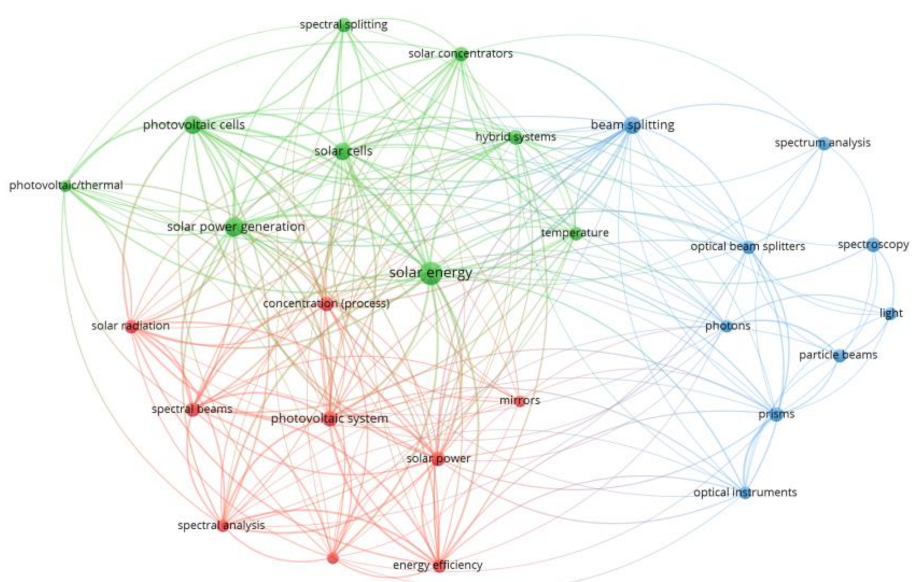


Figure 23: Schematic diagram of visualization analysis.

Table 1: Details in Researches of SBS Technology

	Author	Method[a]	Filter TYPE	Filter Material	Cell Types
1985	Soule *et al*. [76]	T&E	solid interference filters	dielectric-Au-dielectric multilayer	Si
1999	Stojanoff *et al*. [100]	TV	holographic filters	dichromat gelatin on glass or plastic film substrata	GaInP; GaAs; AlGaAs; Si
2005	Imenes *et al*. [77]	T&E	solid interference filters	SiO_2/TiO_2	Si
2007	Kostuk *et al*. [105]	TV	luminescent filters	PMMA with a fluorescent dye or a quantum dot mixture	Si
2008	Glenn Rosenberg *et al*. [99]	TV	holographic filters	NE	multiple junction cells
2009	Shou *et al*. [78]	TV	solid interference filters	Nb_2O_5 /SiO_2	Si
2010	Jiang *et al*. [75]	T&E	solid interference filters	Nb_2O_5 / SiO_2	Si
2011	Mitchell *et al*. [73]	TV	solid interference filters	dichroic mirror	GaInP; Si; GaSb
2011	Zhao *et al*. [70]	TV	solid interference filters	dichroic mirror	GaAsP; GaAs/ InGaAs
2011	Khvostikov *et al*. [71]	TV	solid interference filters	dichroic mirror	AlGaAs; GaAs; GaSb
2011	Zhao *et al*. [90]	TV	liquid absorptive filters	NE	Si
2011	Xia *et al*. [103]	EV	holographic filters	NE	GaAs
2012	Yuan *et al*. [72]	TV	solid interference filters	dichroic mirror	GaAS; GaAsP; InGaAs
2014	Tejas *et al*. [79]	T&E	solid interference filters	multilayer optical film	CdTe
2014	Kostuk *et al*. [102]	TV	holographic filters	NE	GaAs
2015	Mojiri *et al*. [29]	T&E	solid interference and liquid absorptive filters	TiO_2/SiO_2/semi-transparent liquid	Si
2015	Winston *et al*. [109, 110]	T&E	photovoltaic filters	GaAs	GaAs
2015	Ji *et al*. [111]	TV	photovoltaic filters	AlGaInP/InGaP/AlGaAs	AlGaInP/InGaP/AlGaAs
2016	An *et al*. [91]	T&E	liquid absorptive filters	polypyrrole nano-fluid	Si
2016	An *et al*. [92]	T&E	liquid absorptive filters	oleylamine solution of Cu_9S_5 nano-particle	Si
2017	Crisostomo *et al*. [96]	T&E	liquid absorptive filters	water-based of core-shell Ag-SiO2nano-particle	Si
2017	K.P. Sibin [87]	T&E	solid interference filters	ITO/Ag/ITO	NE
2018	Hjerrild *et al*. [95]	T&E	liquid absorptive filters	glycerol-based fluid of Ag-SiO_2	NE
2018	Ewasler *et al*. [74]	T&E	solid interference filters	SiO_2/TiO_2; SiO2/Nb_2O_5 or Ta_2O_5	AlGaInP; GaInP; AlGaAs
2015	Kate *et al*. [80-82]	T&E	solid interference filters	organic thin films	Si
2019	Liang *et al*. [83]	T&E	solid interference filters	SiO_2/TiO_2	Si
2019	Wang *et al*. [85]	T&E	solid interference filters	Ge/Nb_2O_3/Na_3AlF_6	c-Si
2019-2020	Han *et al*. [93, 94]	T&E	liquid absorptive filters	glycol nano-fluid of Ag/$CoSO_4$-propylene	Si
2020	Wei *et al*. [88]	T&E	solid interference filters	cermet layer; Si/SiO_2; yttria-stabilized zirconia	NE
2020	Liang *et al*. [107, 108]	TV	photovoltaic filters	TCO(ITO,AZO)	Si
2020	Wang *et al*. [84]	T&E	solid interference filters	Ge/SiO_2	c-Si
2020	Wang *et al*. [86].	T&E	solid interference filters	Ge/Nb_2O_3/Na_3AlF_6	c-Si
2020	Wingert *et al*. [43]	T&E	solid interference filters	dichroic mirror	Si
2021	Walshe *et al*. [97]	T&E	liquid absorptive filters	ethylene glycol of imidazole-phenanthroline groups	Si
2021	Huang *et al*. [98]	T&E	liquid absorptive filters	dimethylamine of silica-coated silver nano-particles/Ag@SiO_2/$CoSO_4$-PG nano-fluid	Si

[a] EV: experimental verification, TV: theoretical verification, T&E: both theoretical and experimental verification
NA: No explanation.

technology has gradually been applied in photovoltaic and photothermal hybrid systems in recent years. It also gives us confidence in the development of SBS technology.

The various filters have different transmittances in visible spectrum which were shown in Figure **24**. It demonstrates that the presented filters have an excellent ability of spectral splitting, the transmittance in visible spectrum of some filters were more than 90%, including solid interference filters [76, 83-85, 87], liquid absorptive filters [29, 90, 91, 97], and photovoltaic filters [111]. However, the poor optical performance parameters still in the any applications of Holographic filters and luminescent filters.

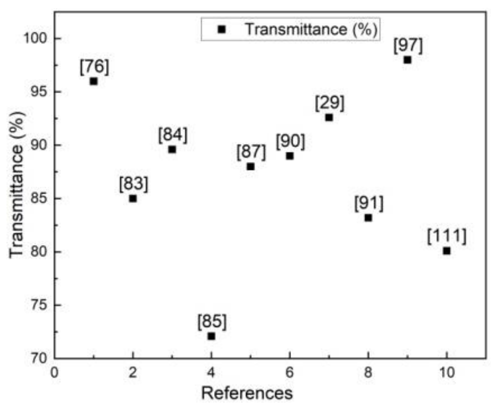


Figure 24: Transmittances in visible spectrum of various filters.

5. CONCLUSIONS

This paper introduces recently research outcomes of the SBS technology for the PV/CST hybrid system. SBS techniques can realize the temperature decoupling of photovoltaic and photothermal and can simultaneously generate electricity and high value thermal energy as well in a PV/CST hybrid system. The development and research trends of the spectral splitting filter used in PV/CST hybrid system have been reviewed. The materials, structure, types, performance advantages and technical obstacles of the spectral splitting filters were presented in detail in the paper and summarized as following:

- The commonly used materials in solid spectral splitting filters are interference thin films such as TiO_2, SiO_2, ITO and other materials which have high sunlight transmission characteristics in the range of visible and near-infrared wavelength. Due to the excellent spectral splitting effect, stable working performance, mature processing technology, the solid spectral splitting filters are widely utilized in PV/CST hybrid system.
- At present, the preparation of the selective absorbing liquid is the key technology for the liquid spectral splitting filters. The nanoparticles such as Ag, Cu and ITO are generally mixed in glycol, glycerol, thermal oil and other fluids to improve the absorptivity at UV and infrared ranges wavelengths and leave the part of spectral response of PV cells. The type of liquid, solubility, nanoparticle layer thickness and the temperature remarkably influence the performance of the liquid spectral splitting filters. Especially, the stability of nanofluids at high temperature is not so good that the further research needs focus on how to improve the working temperature and stability of the liquid spectral splitting filter for PV/CST hybrid system.
- The advantages of the holographic spectral splitting filter and luminescent spectral splitting filter are that the two filters can concentrate and split solar energy by internal reflection and without employing tracking systems. Compared with other kinds of filters, the complicated design and high cost limit the application of the two filters for PV/CST hybrid system.
- With the transparent thin film as a key internal component, the PV cell can be utilized as a spectral splitting filter, which directly achieve SBS functions. However, it is difficult and expensive to manufacture the high-transmittance PV cells at present.

At present, most of the research on spectral splitting filters is still in the laboratory level. It is necessary to establish the entity and experimental models to verify various effects of the spectral splitting filters. Moreover, for the needs of practical applications, the spectral splitting filter and PV cell are packaged together to form a module which will show its advantages in future research. We believe that the SBS technology will have extensive application prospects for combined power and high value of heat in future. This review can help the researchers and practitioners have a better understanding of the SBS technology and features of different spectral splitting filters for the PV/CST hybrid system.

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Conflicts of Interest: We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work; there is no professional or other personal interest of any nature or kind in any product, service, and the company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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