Review

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Review

Solar Spectrum Splitting for Photovoltaic Applications

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Abstract

Photovoltaic (PV) systems are fundamentally limited by spectral mismatch between the solar spectrum and semiconductor band gaps, resulting in thermalization and transmission losses that reduce overall efficiency. This paper presents a critical review of spectral management approaches, focusing on solar spectrum splitting as a means to improve energy conversion. Existing strategies, including multijunction solar cells, optical spectrum splitting, dispersive and diffractive systems, luminescent solar concentrators, hybrid photovoltaic–thermal systems, and photonic filtering, are analyzed and compared. While these approaches improve spectral utilization, they are often constrained by fabrication complexity, alignment sensitivity, angular dependence, or inherent energy losses. A qualitative, integrative literature review methodology is used to evaluate performance, limitations, and implementation feasibility across these technologies. The analysis shows that no current approach simultaneously achieves high efficiency, low complexity, and robust performance under diffuse illumination. Photonic spectrum splitting combined with independently operated photovoltaic channels is identified as a promising direction. However, the absence of experimental validation remains a limitation, and future work should focus on developing compact, alignment-tolerant systems for practical applications.

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1. Introduction

This study examines the design and development of a student-assembled solar spectrum-splitting system that integrates optical filtering with photovoltaic (PV) cells to enhance energy conversion. The system uses accessible optical components, including dichroic filters and photonic wavelength-selective structures, to separate incoming sunlight into multiple spectral bands and route each band to a corresponding solar cell. The objective is to demonstrate a compact, low-cost system capable of producing measurable electrical output while maintaining repeatability and ease of assembly in an instructional or experimental setting.

This work is relevant to the engineering and technical communication communities because it translates a complex, interdisciplinary system that integrates optics, photovoltaics, and electrical systems into a reproducible, clearly documented platform. The project emphasizes accessibility, system-level design clarity, and the communication of engineering trade-offs, enabling both educational use and early-stage research validation.

The following research questions guide this study:

1. How can solar spectrum splitting improve photovoltaic energy conversion compared to conventional approaches?
2. What limitations exist in current spectral management techniques? and,
3. Can a compact, student-assembled system achieve effective spectral separation with measurable electrical output?

The remainder of this article is organized as follows: Section II presents the materials and methodology, Section III examines the results of the literature review, Section IV defines the research gap and objectives, and Section V presents the patent landscape.

2. Materials and Methods

This study adopts a qualitative, integrative literature review methodology to evaluate existing approaches to solar spectrum splitting for photovoltaic applications. The review focuses on identifying, comparing, and critically analyzing major spectral management strategies, including multijunction solar cells, optical spectrum splitting, dispersive and diffractive systems, luminescent solar concentrators, hybrid photovoltaic–thermal systems, and photonic crystal-based filtering.

A. Literature Selection

Relevant literature was identified through academic databases, including IEEE Xplore, ScienceDirect, and Google Scholar, as well as journal publishers such as Elsevier and Springer. Sources were selected based on relevance to photovoltaic spectral management, citation frequency, and contribution to foundational or recent developments in the field. Both classical references and recent peer-reviewed articles were included to capture the evolution of spectrum-splitting technologies.

B. Inclusion Criteria

Studies were included if they:

1. Address spectral mismatches or spectral management in photovoltaic systems,
2. Present or analyze spectrum-splitting techniques or related optical methods,
3. Provide experimental, theoretical, or review-based insights into system performance.

Patent literature was also included to evaluate current technological directions and practical implementations.

C. Analysis Approach

The selected literature was analyzed using a thematic and comparative approach. Technologies were grouped into categories based on their operating principles, including optical filtering, geometric splitting, luminescent conversion, and photonic structures. Each category was evaluated for spectral selectivity, potential efficiency, angular sensitivity, system complexity, and implementation feasibility.

D. Critical Evaluation Framework

A critical evaluation framework was applied to identify strengths, limitations, and trade-offs across different approaches. Emphasis was placed on:

- Optical performance and wavelength selectivity
- Sensitivity to alignment and illumination conditions
- Energy conversion efficiency and loss mechanisms
- System complexity and fabrication requirements
- Suitability for compact and experimentally accessible systems

E. Synthesis

The findings from the literature were synthesized to identify common limitations and gaps in current spectrum-splitting technologies. This synthesis informed the development of a proposed research direction focused on combining photonic wavelength-selective filtering with independently operated photovoltaic channels to improve performance while maintaining practical implementation.

3. Results

A. Fundamental Limitation: Spectral Mismatch

The efficiency of photovoltaic (PV) energy conversion is fundamentally limited by spectral mismatch between the solar spectrum and semiconductor band gaps. Sunlight contains ultraviolet, visible, and infrared photons with a wide range of energies, while a single semiconductor absorber can efficiently convert only a narrow portion of that range. Photons with energy below the band gap pass through the device without generating carriers, while photons with excess energy lose the difference as heat through thermalization [1,2]. Because these losses occur before electrical conversion, they cannot be addressed solely by improving electrical transport within the solar cell.

To address this limitation, researchers have focused on controlling how light reaches the solar cell rather than only modifying the semiconductor itself. These approaches are generally referred to as spectral management techniques, where the goal is to match photon energy to the absorption better before electrical generation occurs [3]. By improving this optical matching, a larger portion of the solar spectrum can be used more effectively.

One of the most direct spectral management strategies is solar spectrum splitting. In this approach, incoming sunlight is divided into multiple wavelength bands, and each band is directed to a device optimized for that specific energy range [4]. This allows high-energy photons to be used by wide band gap materials and lower-energy photons to be utilized by narrow band gap devices, reducing both transmission and thermalization losses.

Compared to multijunction solar cells, which achieve spectral matching internally through stacked layers, spectrum splitting separates the optical and electrical design. This enables independent operation of each photovoltaic channel, greater flexibility in material selection, and simpler system integration. However, it also introduces challenges related to optical alignment, component losses, and system-level integration, which are important considerations in practical implementations.

B. Multijunction Solar Cells: Internal Spectrum Matching

Multijunction solar cells aim to reduce spectral mismatch by incorporating multiple semiconductor layers with different band gaps within a single device [5,6]. Each junction is designed to absorb a specific portion of the solar spectrum, allowing more efficient use of incoming photons compared with single-junction cells. By distributing the spectrum across multiple absorbers, these devices can achieve significantly higher conversion efficiencies.

However, multijunction cells are typically connected electrically in series, which means the same current must pass through every layer. An illustration of this design is shown in Figure 1. If one junction produces less current due to changes in the solar spectrum, temperature, or material properties, it limits the performance of the entire device [5].

This constraint, known as current matching, is a major challenge in maintaining optimal performance under real-world operating conditions.

In addition to electrical constraints, multijunction devices require complex fabrication processes, including precise material growth, lattice matching, and layer alignment. These requirements increase cost and limit scalability, especially for experimental or modular systems. As a result, while multijunction cells demonstrate very high efficiency, their complexity motivates the exploration of alternative approaches that can achieve spectral matching outside the semiconductor structure.

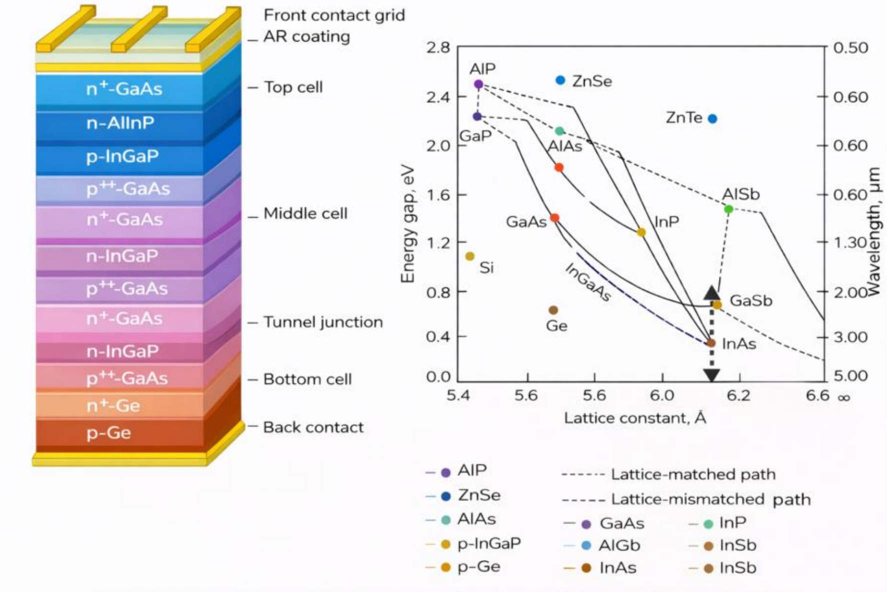

Figure 1. Multilayer Solar Cell and Energy Graph (recreated from [1]).

C. Optical Spectrum Splitting

Instead of stacking semiconductors, optical spectrum splitting separates wavelengths before the energy conversion process occurs. In this approach, optical components such as thin-film interference filters and dichroic mirrors are used to selectively reflect and transmit specific wavelength bands [4,7]. Each portion of the spectrum is then directed to a photovoltaic device that is better matched to that energy range. Hybrid receiver systems have shown that routing selected wavelengths to dedicated absorbers can improve spectral utilization while also reducing thermal loading on the photovoltaic device [8].

A key advantage of this approach is that each photovoltaic channel can operate independently. Unlike multijunction cells, where all layers are electrically linked, spectrum-splitting systems avoid current-matching constraints and allow each device to operate closer to its optimal performance point. This provides greater flexibility in system design and material selection

However, thin-film interference filters are sensitive to the angle of incoming light. The cutoff wavelength shifts with the angle of incidence, which can reduce spectral selectivity and overall system performance under non-ideal conditions [9]. Because outdoor sunlight is often diffused and not perfectly aligned, this angular sensitivity becomes a significant practical limitation for real-world applications.

D. Geometric Splitting Approaches

Other optical methods separate wavelengths spatially rather than through reflection-based filtering. Dispersive and diffractive elements, such as prisms and gratings, use wavelength-dependent refraction or diffraction to route different portions of the spectrum to separate physical locations [10,11]. In these systems, shorter and longer wavelengths follow different paths, allowing each band to be directed toward a dedicated photovoltaic receiver. A diagram of this process is depicted in Figure 2.

Waveguide-based designs extend this concept by transporting selected spectral components laterally to different receivers. This can enable more compact system layouts and integrated designs, but it also introduces additional losses due to imperfect coupling and propagation within the waveguide structure [12].

While these approaches demonstrate that spatial spectral allocation is feasible, they require precise optical alignment to function effectively. Small changes in geometry, positioning, or incident light conditions can significantly alter how wavelengths are distributed across the receivers. This

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sensitivity reduces system repeatability and robustness, particularly in compact or student-built systems where maintaining precise alignment is more difficult.

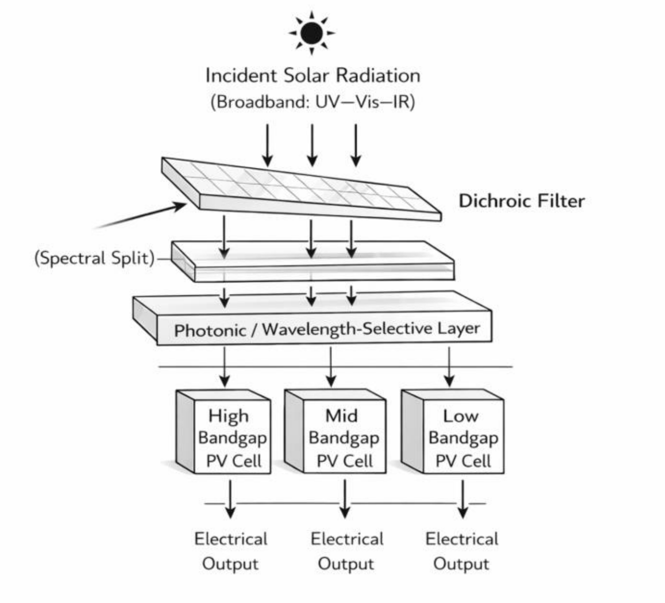

Figure 2. Solar Energy System for Wavelength-Selective Photovoltaics.

E. Hybrid PV-Thermal Systems

Another strategy is to use portions of the solar spectrum as heat instead of converting all photons into electricity. Hybrid photovoltaic–thermal (PV-T) systems, diagram shown in Figure 3, route part of the incoming radiation to photovoltaic cells while directing the remaining wavelengths to thermal absorbers [13,14]. This approach increases total energy utilization by capturing both electrical and thermal energy from the same system.

However, while PV-T systems improve overall energy efficiency, they do not directly increase electrical output. The thermal energy produced is considered lower-quality energy compared to electrical energy because it has lower energy and is less flexible for practical use. Converting heat back into electricity requires additional processes, such as thermodynamic cycles, which introduce further losses and increase system complexity.

In contrast, photovoltaic systems convert photon energy directly into electrical energy through the photovoltaic effect, allowing for immediate and efficient use in electrical systems. This direct conversion avoids intermediate steps and preserves more of the original energy quality. As a result, while PV-T systems are beneficial for combined heat and power applications, they are less effective when the primary goal is maximizing electrical generation.

Additionally, integrating both thermal and electrical components increases system design complexity, requiring careful thermal management, additional materials, and more complex system integration. These factors make PV-T systems less suitable for compact, modular, or student-built applications where simplicity and direct electrical output are priorities.

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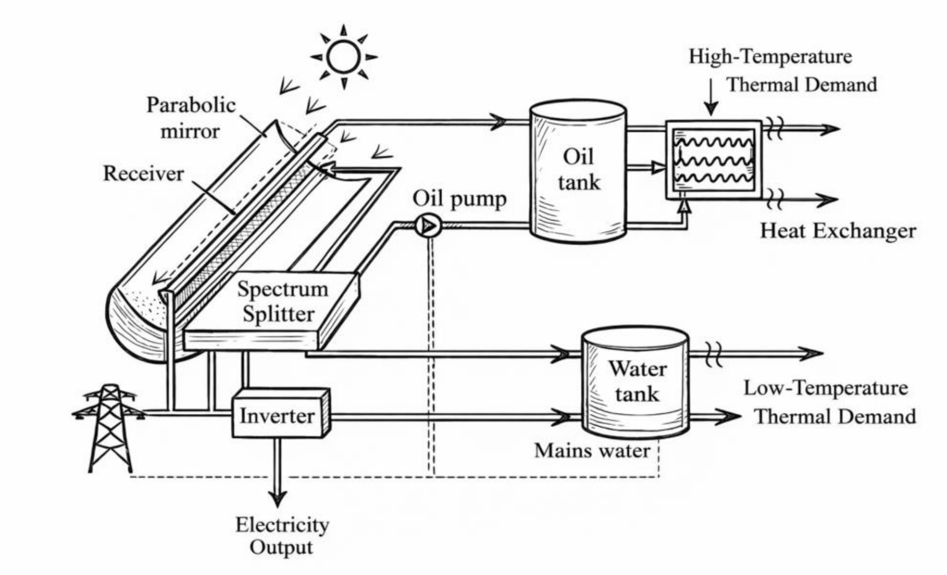

Figure 3. Solar Hybrid Energy System Diagram.

F. Luminescent Solar Concentrators

Luminescent solar concentrators (LSCs) improve angular tolerance by absorbing incoming photons within a luminescent material and re-emitting them at longer wavelengths in random directions [15,16]. The re-emitted light is then guided through the material by total internal reflection toward photovoltaic cells located at the edges. Because the absorption process does not depend strongly on the angle of incoming light, LSCs can operate effectively under diffuse illumination, making them attractive for real-world outdoor conditions where sunlight is not perfectly collimated. A diagram of this process is demonstrated in Figure 4.

However, this process introduces several inherent losses. First, during re-emission, photons are shifted to lower energy (longer wavelength), a phenomenon known as the Stokes shift. This reduces the maximum achievable electrical output because some of the original photon energy is lost before conversion. Additionally, not all absorbed photons are successfully guided to the photovoltaic cells—some are lost through escape cone losses, reabsorption, or non-radiative recombination within the material.

As a result, while LSCs improve optical collection and angular tolerance, they reduce the overall energy quality of the photons reaching the solar cell. Unlike direct photovoltaic conversion, where photon energy is converted immediately into electrical energy, LSC systems rely on an intermediate optical process that introduces additional inefficiencies. This trade-off highlights a key challenge: improving light capture under diffuse conditions often comes at the cost of reduced electrical conversion efficiency.

G. Photonic Crystal Spectral Filtering

Photonic crystal structures control light through a periodic variation in refractive index, which creates wavelength-selective optical behavior [17]. This periodic structure forms photonic band gaps, where certain wavelengths are allowed to propagate while others are reflected or suppressed. As a result, photonic crystals can selectively transmit or reflect specific portions of the solar spectrum without relying entirely on geometric beam separation or angle-dependent filtering [18,19].

Because this filtering is governed by optical modes within the structure rather than simple ray direction, photonic crystals can maintain wavelength selectivity even when the angle of incoming light changes. This makes them less sensitive to alignment compared to thin-film interference filters or dispersive optical elements, which often require precise orientation to function effectively.

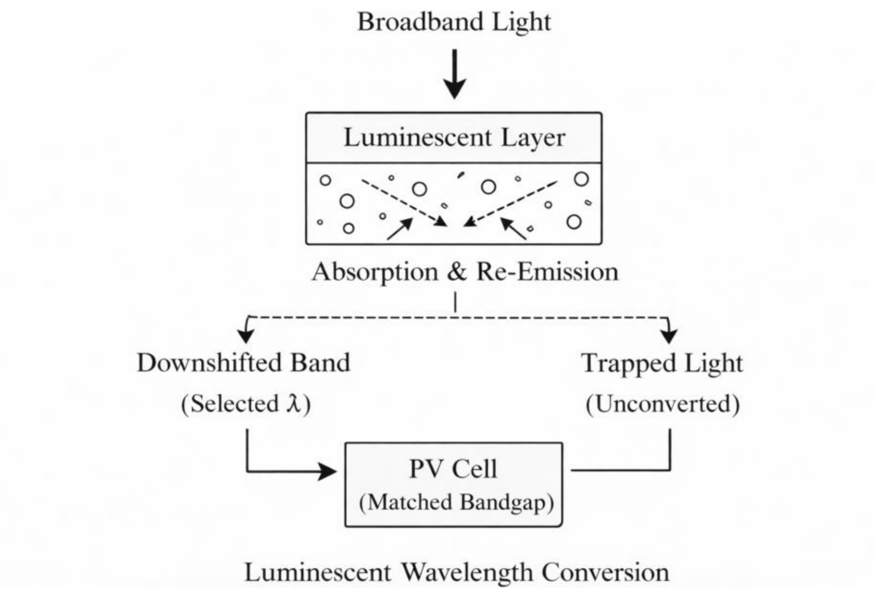

Figure 4. Luminescent Wavelength Conversion Diagram.

For spectrum splitting applications, this behavior offers a significant advantage. Photonic crystal filters can separate wavelengths while preserving the light's direction toward photovoltaic receivers, enabling direct electrical conversion without intermediate energy-loss processes. At the same time, their reduced sensitivity to incidence angle allows them to operate more reliably under diffuse or partially scattered sunlight conditions.

This combination of wavelength selectivity, angular tolerance, and direct photon-to-electricity conversion makes photonic crystal filtering particularly attractive for compact, modular systems. In contrast to many existing approaches, these structures offer a pathway toward simplified alignment, improved robustness, and practical implementation in student-built or small-scale experimental platforms.

H. Electrical Integration After Spectral Separation

After the spectrum is split, each photovoltaic channel receives a different portion of the solar spectrum and therefore produces different voltage and current outputs. This occurs because photon energy directly influences the electrical characteristics of each device, with higher-energy photons generally contributing to higher voltages and lower-energy photons contributing to different current levels.

If the channels are connected in series, mismatch losses can occur, similar to those seen in multijunction solar cells. In this configuration, the total current is limited by the lowest-performing channel, which reduces the overall system output [5]. Alternatively, if the channels are connected in parallel without proper design, differences in voltage between channels can lead to imbalance, power loss, or even reverse current flow, further reducing efficiency.

To address these issues, the independent operation of each photovoltaic channel is often preferred. By allowing each channel to operate at its own maximum power point, the system can maximize energy extraction from each portion of the spectrum [20,21]. This typically requires additional power electronics, such as separate maximum power point tracking (MPPT) or DC–DC conversion for each channel.

Therefore, spectrum splitting is not only an optical design problem but also an electrical system integration challenge. Effective implementation requires coordination between optical filtering and electrical architecture to ensure that the benefits of spectral separation are not lost due to electrical mismatch or inefficient power management.

4. Discussion

The reviewed literature shows that significant progress has been made in improving photovoltaic efficiency through spectral management, yet no single approach simultaneously achieves high electrical efficiency, low fabrication complexity, and reliable operation under non-ideal illumination conditions.

Multijunction solar cells provide strong spectral matching but require complex fabrication and internal current matching constraints. Thin-film interference spectrum splitters allow independent receivers but are sensitive to incidence angle and therefore depend on well-collimated sunlight. Dispersive and diffractive splitters spatially separate wavelengths but require precise optical alignment. Luminescent concentrators improve angular tolerance but reduce photon energy during re-emission. Hybrid photovoltaic–thermal systems increase total energy utilization but introduce additional conversion steps and do not maximize direct electrical output.

A key limitation common to many spectrum splitting systems is their dependence on beam-like illumination. Many designs are optimized for concentrator conditions and degrade when exposed to diffuse or partially scattered sunlight. Additionally, several approaches focus primarily on optical separation while treating electrical integration as secondary, which can reintroduce mismatch losses like multijunction devices.

Therefore, a practical gap exists between high-performance laboratory spectrum splitting concepts and compact, experimentally accessible systems that operate reliably in realistic illumination environments. An effective system should:

1. maintain wavelength selectivity under varying incidence angles,
2. generate direct electrical output in multiple channels,
3. minimize electrical interference between channels, and
4. be implementable using accessible fabrication methods.

Existing approaches improve spectral utilization, but each introduces a key limitation. Multijunction solar cells require complex fabrication and strict current matching. Thin-film interference filters depend on well-collimated light and lose performance under varying angles. Geometric splitting methods rely on precise optical alignment, while luminescent systems introduce energy losses through re-emission. Hybrid photovoltaic–thermal systems increase total energy utilization but add system complexity and do not maximize direct electrical output.

A system that combines wavelength-selective photonic filtering with independently operated photovoltaic channels, as illustrated in Figure 5, provides a promising alternative. By separating spectral control from the semiconductor and enabling direct photon-to-electricity conversion, this approach can maintain high energy quality while reducing optical and electrical mismatch losses. In addition, the use of photonic structures improves tolerance to diffuse illumination, while independent electrical operation allows each channel to perform at its optimal point.

Together, these features support a modular and scalable system design that is better suited for compact, experimentally accessible platforms. This makes the approach particularly attractive for applications requiring simplified fabrication, improved robustness, and reliable performance outside controlled laboratory conditions.

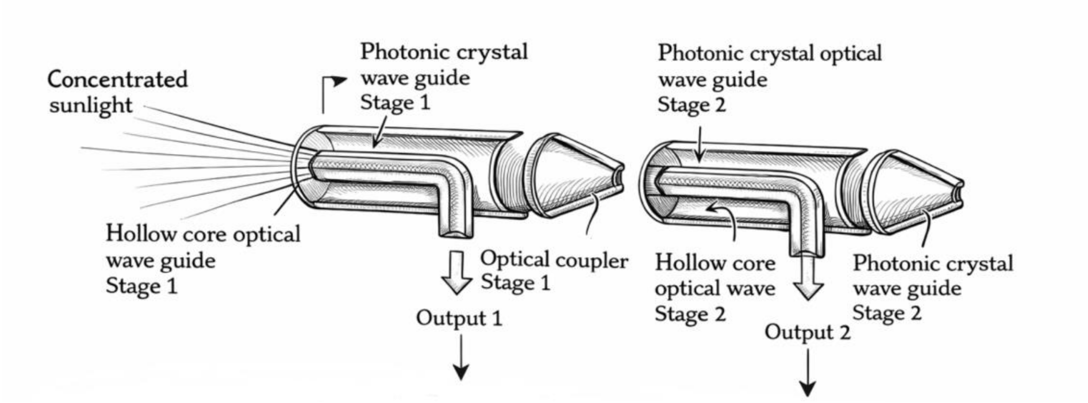

Figure 5. 3D Figure for Parallel Integrated Solar Cell Circuit (3D AI-generated model).

The objective of this research is to design and experimentally validate a compact solar spectrum splitting module that integrates wavelength-selective optical filtering with independently operated photovoltaic receivers. The system will emphasize tolerance to diffuse illumination and repeatable assembly using accessible fabrication techniques. By combining photonic filtering concepts with modular electrical integration, the work aims to demonstrate a practical architecture for multiband photovoltaic conversion that bridges the gap between advanced spectral management theory and deployable small-scale systems.

5. Patents

The patent landscape for solar spectrum splitting systems reflects a wide range of approaches aimed at improving photovoltaic efficiency through wavelength-selective routing and multi-receiver architecture. Existing patents primarily focus on optical configurations that separate incoming solar radiation into discrete spectral bands and direct each band toward photovoltaic cells or hybrid energy conversion systems optimized for those wavelengths. Recreated illustrations for each patent are shown in Figure 6.

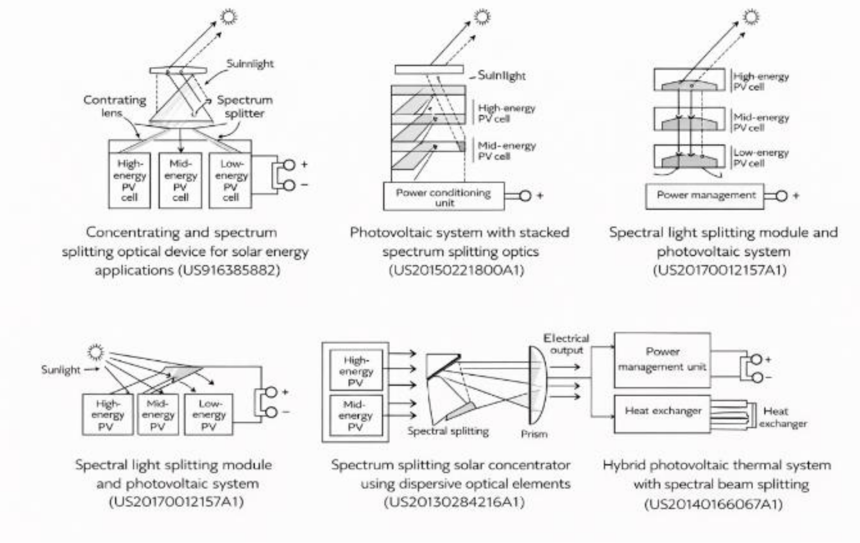

Figure 6. Patent Scope Recreated Illustrations.

One representative example is US9163858B2 [22], which describes an optical system capable of both concentrating and spectrally splitting incident radiation. The design integrates optical elements such as lenses and wavelength-selective filters to direct specific spectral bands toward corresponding photovoltaic receivers. While this approach demonstrates high efficiency potential, it relies on concentrated solar input and precise optical alignment, which may limit its applicability for low-cost or student-assembled systems.

Another relevant patent is US20150221800A1 [23], which proposes a stacked optical architecture consisting of multiple diffractive or filtering layers arranged in series. Each layer selectively separates a portion of the solar spectrum and routes it to photovoltaic cells with matching band gaps. This multi-stage configuration enables fine spectral control but introduces increased system complexity, fabrication challenges, and alignment sensitivity.

The patent US20170012157A1 [24] presents a modular approach to spectral splitting, where a compact optical unit is integrated directly with photovoltaic devices. This design emphasizes system-level packaging and integration, making it more applicable to practical implementations. However, the module still relies on precisely engineered optical components, which may not be easily reproducible in an instructional or low-cost laboratory setting.

A different approach is described in US20130284216A1 [25], which uses dispersive optics such as prisms or gratings to spatially separate wavelengths. This method avoids multilayer thin-film coatings and instead relies on chromatic dispersion to achieve spectral separation. While it is potentially easier to measure at scale, dispersive systems often require careful geometric alignment between the optical element and multiple receivers, increasing mechanical complexity.

Finally, US20140166067A1 [26] demonstrates the use of spectrum splitting in hybrid PV thermal (PV-T) applications. In this system, a wavelength-selective filter reflects the photovoltaically active portion of the spectrum toward a solar cell while transmitting longer wavelengths to a thermal absorber. This approach highlights the broader application of spectral splitting beyond purely electrical generation, but it introduces additional system layers and thermal management considerations.

Across these patents, several common trends emerge. First, many designs prioritize high efficiency through concentration, multi-stage filtering, or precise spectral control. Second, these systems often rely on specialized optical components and tight alignment tolerances. Third, integration with photovoltaic devices is typically optimized for performance rather than accessibility or ease of assembly.

Despite the maturity of spectrum splitting concepts in patent literature, there remains a gap in systems designed specifically for low-cost fabrication, modular assembly, and repeatable experimental validation. Most patented designs are not optimized for student use or instructional environments, where simplicity, robustness, and reproducibility are critical. The proposed project addresses this gap by developing a compact, student-assembled spectrum-splitting module that prioritizes accessible materials, simplified alignment, and direct electrical measurement. In doing so, the work translates established spectrum-splitting principles into a practical engineering platform suitable for both research prototyping and education.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

LSC	Luminescent solar concentrators
PV-T	Hybrid photovoltaic–thermal
PV	Photovoltaic
MPPT	Maximum power point tracking

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