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Spectral-splitting PV-thermal Collectors based on optical filters of selective reflectors and selective absorbers

Summary

Spectral-splitting photovoltaic-thermal (PVT) collectors enable simultaneous electricity and heat generation through wavelength-selective optical management. We present two complementary architectures based on a selective reflector and a selective absorber. The selective reflector employs a dielectric Bragg mirror to reflect λ < 870 nm to a concentrated GaAs photovoltaic cell while transmitting infrared radiation to a thermally insulated absorber, achieving 6.5% electrical efficiency and 8.8% thermal efficiency at 80 °C with a stagnation temperature of 209 °C. The selective absorber integrates a UV-visible absorbing film and water-based infrared absorption to simultaneously filter and harvest thermal energy, reaching fluid temperatures up to 86.8 °C while reducing photovoltaic operating temperature. These results demonstrate tunable spectral control for decoupled hybrid solar energy conversion.

Keywords: spectral splitting, photovoltaic-thermal collectors, selective reflector, selective absorber

Field of application for the findings: Industrial processes, buildings, and concentrated solar applications.

Addressed audience: Researchers working on photovoltaic, solar-thermal, and hybrid solar energy systems.

1. Introduction

The global transition toward carbon-neutral energy systems requires simultaneous decarbonization of both electricity and heat sectors. While photovoltaic (PV) technologies have achieved remarkable progress in electrical conversion efficiency, more than half of final energy demand worldwide is associated with thermal applications, including space heating, domestic hot water, and industrial process heat. Hybrid photovoltaic-thermal (PVT) collectors attempt to address both demands by thermally coupling a PV module to a heat exchanger [1, 2]. However, such direct coupling imposes a fundamental trade-off: increasing thermal output temperature elevates PV operating temperature, thereby reducing electrical performance. As a result, most commercial PVT systems are limited to low-temperature applications below ~85 °C.

Spectral-splitting PVT collectors provide an alternative pathway by optically separating the solar spectrum before energy conversion [3–5]. High-energy photons are directed to the photovoltaic cell, while lower-energy photons are harvested thermally, enabling thermal–electrical decoupling and higher operating temperatures. Optical filters are central to this approach and can be broadly categorized into selective reflectors and selective absorbers [6, 7].

In this work, we present two complementary spectral-splitting architectures [8, 9]. The first employs a dielectric Bragg mirror as a selective reflector under concentrated illumination, achieving high-temperature heat generation with stagnation temperatures exceeding 200 °C. The second utilizes a hybrid liquid-solid selective absorber that simultaneously filters and absorbs unused spectral bands while transferring heat to a working fluid. By systematically comparing these two approaches, we highlight their optical principles, thermal performance, and integration challenges, providing design guidelines for next-generation hybrid solar energy systems.

2. Experimental setup and results

Two spectral-splitting photovoltaic-thermal (PVT) architectures based on a selective reflector and a selective absorber are shown in Figure 1. As illustrated in Fig. 1a, the selective reflector configuration employs a dielectric Bragg mirror positioned under a Fresnel concentrator [8]. The mirror reflects short-wavelength radiation toward a concentrated GaAs photovoltaic cell with active gas cooling, while transmitting longer wavelengths to a thermally insulated solar-thermal absorber. This optical separation enables spatial decoupling of heat and electricity generation. The system was evaluated under concentrated illumination (geometric factor ~100). The thermal absorber, placed inside a vacuum enclosure to minimize convective and radiative losses, reached stagnation temperatures of 209 °C. A thermal efficiency of 8.8% was measured at 80 °C, demonstrating the capability for high-temperature heat generation under spectral splitting.

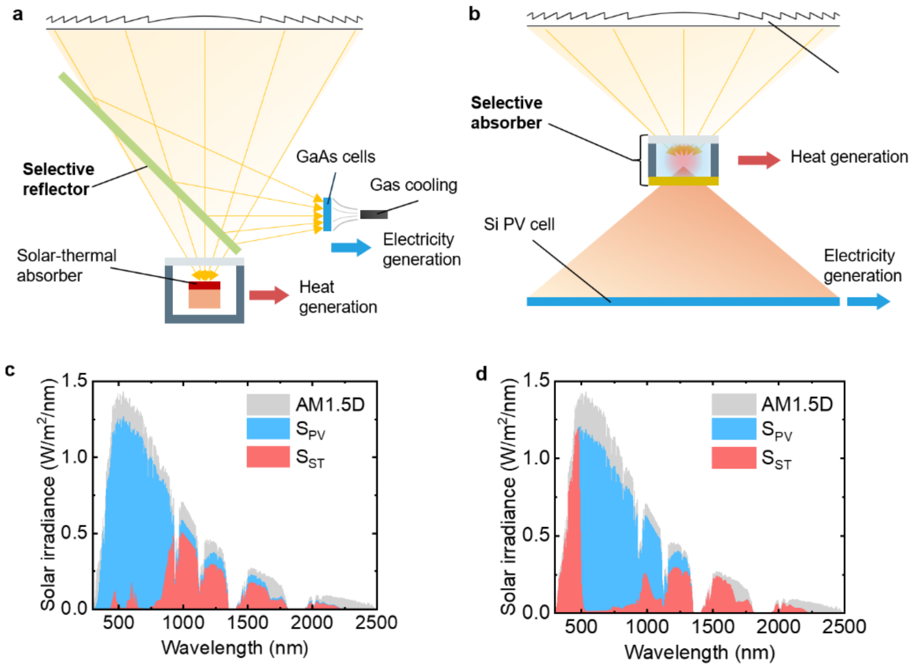

Figure 1. Comparison of spectral-splitting PVT architectures based on a selective reflector and a selective absorber. (a) A dielectric Bragg mirror reflects short-wavelength radiation to a concentrated GaAs photovoltaic cell while transmitting longer wavelengths to a thermally insulated solar-thermal absorber, enabling spatial separation of electricity and heat generation. (b) A hybrid liquid-solid selective absorber simultaneously filters and absorbs ultraviolet-visible and infrared radiation for heat generation, transmitting the useful spectral window to a silicon photovoltaic cell. (c–d) Spectrally resolved AM1.5D solar irradiance distribution showing the portions directed to photovoltaic conversion (SPV) and solar-thermal harvesting (SST) for the selective reflector (c) and selective absorber (d) configurations.

Figure 1b presents the selective absorber configuration [9]. Here, a hybrid liquid-solid optical filter simultaneously performs wavelength filtering and thermal absorption. A UV-visible selective absorbing film removes high-energy photons, while a water layer absorbs near-infrared radiation. The remaining mid-spectrum photons are transmitted to a silicon photovoltaic cell positioned below the filter. Unlike the reflector-based design, spectral management and heat capture occur within the same component. Under concentrated testing conditions, the working fluid reached temperatures up to 86.8 °C, while the photovoltaic operating temperature was reduced due to upstream spectral filtering.

Figures 1c and 1d show the spectrally resolved solar irradiance distribution under AM1.5D conditions for both systems. In the selective reflector case (Fig. 1c), wavelengths below approximately 870 nm are directed to the photovoltaic cell (SPV), while longer wavelengths are transmitted to the solar-thermal receiver (SST). In contrast, the selective absorber system (Fig. 1d) absorbs ultraviolet-visible and infrared bands for thermal generation, transmitting only the useful spectral window to the photovoltaic cell. These results demonstrate two distinct yet complementary spectral management strategies for thermally decoupled hybrid solar energy conversion.

3. Conclusion

This work demonstrates two complementary spectral-splitting photovoltaic-thermal (PVT) collector architectures based on selective reflectors and selective absorbers. Both approaches enable optical decoupling of thermal and electrical conversion pathways, addressing the intrinsic temperature-performance trade-off of conventional PVT systems. The selective reflector configuration, employing a dielectric Bragg mirror under concentrated illumination, achieves high-temperature heat generation with stagnation temperatures exceeding 200 °C, highlighting its potential for medium- to high-grade thermal applications. The selective absorber configuration integrates wavelength filtering and heat capture within a hybrid liquid-solid optical filter, offering structural simplicity and stable operation while effectively reducing photovoltaic operating temperature. Comparative analysis reveals that reflector-based systems favor higher operating temperatures through spatial separation and minimized filter absorption, whereas absorber-based systems provide compact integration and reduced optical complexity. In both cases, optical losses, angular effects under concentration, and thermal management remain critical design considerations. These findings provide practical guidelines for tunable spectral control in next-generation hybrid solar energy systems and outline pathways toward improved overall efficiency and scalability.

4. References

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