

# Nanocomposite Films for Spectral Conversion-enhanced Thermal Control of Solar Photovoltaic Cells

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**Abstract.** The combustion of fossil fuels releases harmful greenhouse gases, acidic substances and other pollutants, leading to global warming, acid rain, air pollution, ecosystem damage, and more frequent extreme weather events, severely impacting the environment and human health. To address these issues, there is an increasingly growing push for renewable energy solutions. Solar photovoltaic (PV) systems stand out as a promising renewable technology. However, the efficiency of solar PV systems is significantly affected by heat accumulation during operation. To tackle this challenge, nanocomposite films, which integrate nanoparticles into polymer matrices, offer an effective solution by improving thermal management. These films can manipulate photon energies through processes like Down-conversion, Down-shifting, and up conversion, optimizing light energy utilization and reducing heat. Research examples demonstrate the effectiveness of various nanomaterials in enhancing solar cell performance. Future work should focus on optimizing synthesis techniques, exploring new materials, and developing scalable manufacturing methods for commercial application.

**Keywords:** Nanocomposite Films; Spectral Conversion; Thermal Control; Solar Cells.

## 1. Introduction

The combustion of fossil fuels releases a large amount of greenhouse gases and pollutants, leading to global climate warming, worsening air pollution, damage to ecosystems, and an increased frequency of extreme weather events, causing serious impacts on the environment and human health. According to the Global Energy Sector roadmap, by 2050, the global community needs to achieve net-zero greenhouse gas emissions, which means a comprehensive transformation of the energy system, with renewable energy becoming the dominant source and a significant reduction in the use of fossil fuels. In the global electricity sector, the share of renewable energy is projected to rise from 30% in 2023 to 46% in 2030, with solar energy accounting for nearly 55% of this increase. TrendForce predicts that global photovoltaic (PV) installed capacity will reach 596GW in 2025, up 6.0% year-on-year [1]. Additionally, the investment in solar PV now surpasses all other generation technologies combined. This indicates the potential of solar PV as a renewable technology to transform the energy landscape and drive sustainable development.

Solar photovoltaic systems use sunshine to generate power. However, only photons with energy around the semiconductor band gap can be efficiently used by traditional single-junction semiconductor solar cells. Photons with energy below the band gap are not absorbed and do not contribute to the production of carriers. The thermalization of the produced electrons causes the surplus energy to be wasted even though photons with energy greater than the band gap are absorbed [2]. Approximately 80% of the total solar energy is transformed into heat and absorbed by the PV cells or dissipated into the environment [3]. The efficiency of the solar cell is closely related to its surface temperature. For every 1°C rise in temperature, the electrical efficiency of a PV panel drops by roughly 0.45% [4]. Thus, the development of strategies to mitigate heat accumulation in solar panels during operation can significantly enhance their photoelectric conversion efficiency, leading to increased power output.

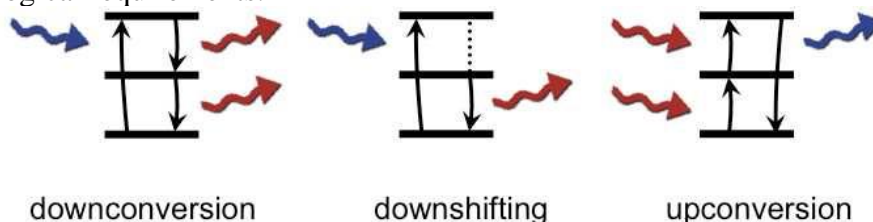
One promising solution to this challenge is the application of nanocomposite films, which offer unique advantages in thermal management and overall performance enhancement for solar PV systems. Nanocomposite films, which integrate nanoparticles into polymer matrices, have emerged

as a powerful tool for improving the thermal and electrical properties of solar PV panels. Additionally, their lightweight and flexible nature makes them suitable for various PV applications, from large-scale solar farms to integrated building materials. For example, recent studies have demonstrated that incorporating specific nanoparticles, such as carbon nanotubes or metal oxides, into these films can significantly reduce the operating temperature of PV panels. This not only improves the efficiency of the panels but also extends their operational lifespan. Moreover, the use of nanocomposite films can also enhance the mechanical durability and weather resistance of solar PV panels, making them more resilient to environmental factors such as dust, humidity, and UV radiation. Therefore, the application of nanocomposite films in solar PV panels represents a significant step forward in addressing the thermal management challenges faced by current solar technologies. By leveraging the unique properties of nanomaterials, these films offer a multifunctional solution that can significantly enhance the efficiency, durability, and overall performance of solar PV systems, thereby driving further progress in the renewable energy sector.

## 2. Spectral Conversion Mechanisms and Applications

### 2.1. Types of Spectral Conversion

In the process of down-conversion (DC), also known as “quantum cutting”, incoming high-energy photons are converted into two or more low-energy photons. Down-shifting (DS) is similar to Down-conversion but with a key difference: only a single photon is emitted in DS. In contrast, upconversion (UC) is the process of converting two or more low-energy (sub-band gap) photons into a single high-energy photon. These processes are crucial for manipulating photon energies in various optoelectronic applications, allowing for enhanced device performance and efficiency. Fig. 1 illustrates these concepts, highlighting how DC, DS, and UC enable the modification of light wavelength to meet specific technological requirements.



**Fig.1** Energy diagrams illustrating photon adsorption and down-conversion, down-shifting and upconversion[2].

### 2.2. Principles

Down-conversion (DC) is a photon energy conversion process that transforms high-energy photons into multiple low-energy ones. Lanthanide ions (e.g.,  $\text{Pr}^{3+}$  and  $\text{Gd}^{3+}$ ), with their rich energy level structures, are often used as dopants. They can effectively absorb high-energy photons (e.g., 185nm vacuum ultraviolet photons) that are captured by a host material (e.g.,  $\text{YF}_3$ ), and convert them into low-energy photons (e.g., 408nm and 620nm visible photons) suitable for solar cells. This conversion occurs through multi-step energy level transitions of the lanthanide ions. For instance,  $\text{Pr}^{3+}$  ions transition from the  $^1\text{S}_0$  state to the  $^3\text{P}_1$  state (emitting a 408nm photon), then to the  $^3\text{F}_2$  state (emitting a 620nm photon). This process allows one high-energy photon to produce multiple low-energy photons, achieving a quantum efficiency over 1. In solar cells, these low-energy photons are more efficiently absorbed and converted into electricity, reducing energy loss and boosting conversion efficiency.

Down-shifting (DS) is a photon energy conversion process that transforms high-energy photons (e.g., blue or UV) into low-energy ones (e.g., red or near-infrared). DS can be used to overcome the poor blue response of solar cells. By shifting the incident spectrum to wavelengths that the solar cell can absorb more effectively, the overall conversion efficiency can be increased by about 10%. Here's

how it works: When a high-energy photon is absorbed by specific ions or molecules in the material, the energy is transferred to their excited states. These excited ions or molecules then release energy through energy level transitions, emitting a low-energy photon. As some energy is lost as heat in this process, the quantum efficiency is usually below 1. DS technology improves the utilization efficiency of high-energy photons in solar cells. By converting them into low-energy photons that solar cells can absorb more readily, it boosts the cells' overall efficiency. New organic dyes with high LQE and better re-absorption properties, as well as quantum dots with adjustable emission wavelengths, have been used in LSCs and have shown advantages. Luminous ions, including transition metal and lanthanide ions, are also alternatives for LSCs. They can achieve efficient luminescence through specific transitions. To efficiently convert visible light into narrow band near-infrared emission, two schemes can be used: one based on a single ion with strong broadband absorption in the visible range, and the other involving a combination of two ions.

Upconversion is a photon energy conversion process that transforms low-energy photons (e.g., infrared) into high-energy ones (e.g., visible or UV). When low-energy photons are absorbed by specific ions or molecules in the material, they undergo multi-step energy transfer and level transitions to emit high-energy photons. This process often combines the energy of two or more low-energy photons to emit one high-energy photon. The technology can convert low-energy photons, otherwise unusable by solar cells, into high-energy photons that the cells can utilize, thus enhancing overall conversion efficiency. Common upconversion mechanisms include energy transfer upconversion (ETU) and two-step absorption (ground state absorption followed by excited state absorption). For example, rare earth ion pairs (like  $\text{Yb}^{3+}$  and  $\text{Er}^{3+}$ ) show high efficiency in up conversion, converting low-energy photons to high-energy ones through multi-step level transitions.

### 2.3. Applications of Nanocomposite Films in Spectral Conversion

#### 2.3.1 Down Conversion

Spectral conversion is the process of transforming high-energy photons into low-energy ones using optical materials to achieve spectral down conversion. This mechanism is crucial in optoelectronics and renewable energy as it broadens the spectral response of photoelectric devices and enhances light energy utilization. Recently, many research teams have focused on developing new spectral conversion materials to achieve efficient down conversion or quantum cutting, thereby optimizing device response and utilization of specific light bands.

Polymer nanocomposite spectral downconverters for UV sensing were developed[5]. They synthesized two types of nanoparticles embedded in a colorless polyimide matrix: CdSe/ZnS core-shell quantum dots and rare earth-doped lead halide perovskite quantum dots. These nanoparticles can efficiently down-convert UV radiation into visible and near-infrared light, matching the spectral responsivity of silicon avalanche photodiodes with photoluminescence quantum yields of 50-190%. The CdSe/ZnS quantum dots convert UV to visible light via a down-shifting mechanism with a red peak at 631nm. The perovskite quantum dots, doped with  $\text{Yb}^{3+}$ , emit in the near-infrared with a peak at 980nm through down conversion or quantum cutting mechanisms. The team used pulsed laser deposition to disperse these nanoparticles uniformly in a polyimide solution and coat them onto transparent substrates. The resulting films significantly enhanced the UV sensitivity of silicon photodetectors, increasing the short circuit current by 4.8% and the output power from 0.929 mW to 0.981 mW. This work offers new materials and methods for high-performance UV detection and free-space optical communication.

The application of rare earth doped perovskites for efficient solar sub-spectral conversion is mainly based on the synthesis of  $\text{CsPbCl}_x\text{Br}_{1-x}$ :  $\text{Yb}^{3+}$  nanoparticles and thin films by thermal injection and two-stage spin casting methods [6]. The nanoparticles have a good crystalline structure and quantum cutting properties, converting UV light to near infrared, while the films emit in the visible range but with low infrared efficiency. These findings offer new material options for efficient solar power and green energy technologies, with future work focusing on enhancing near-infrared emission efficiency for practical applications.

Lin et al. have developed a new broadband near-infrared quantum cutting (QC) phosphor,  $\text{CaTiO}_3:\text{Yb}^{3+}, \text{Bi}^{3+}$  [7]. It efficiently converts 300-480nm ultraviolet blue light into around 1000nm near-infrared light, which is of great significance for enhancing the performance of crystalline silicon (cSi) solar cells. Co-doping with 15%  $\text{Bi}^{3+}$  ions has increased the near-infrared integrated emission intensity of  $\text{Yb}^{3+}$  by tenfold, greatly improving the utilization efficiency of this wavelength band's light by solar cells.

### 2.3.2 Down Shifting

A novel bifunctional silica coating was developed by in situ generation of  $\text{YVO}_4:\text{Eu}^{3+}, \text{Bi}^{3+}$  phosphors in silica antireflective coating (ARC)[8]. This coating not only reduces reflection but also converts UV light to visible light through downshifting, enhancing solar cell efficiency and stability. The coating achieved an average transmittance of 94.99% in the 280-1,200nm band. On this basis, Ag NP-decorated  $\text{YVO}_4$  was integrated into SHJ solar cells using the LSPR effect [9]. This LSPR-enhanced down shifting reduced PCE degradation by approximately 0.54% under 45 kWh of UV irradiation, indicating enhanced UV absorption efficiency and reduced thermalization of generated electrons. Consequently, this approach mitigates solar cell heat accumulation, boosting efficiency and stability.

$\text{Cs}_4\text{PbBr}_6$  colloidal nanoparticles were synthesized using the reverse microemulsion method and polyvinyl alcohol (PVA) and tetrabutylammonium bromide (TOABr) were introduced as additives during the synthesis process to optimize the dispersibility and optical properties of the particles [10]. These modifications increased the photoluminescence quantum yield of  $\text{Cs}_4\text{PbBr}_6$  nanoparticles from about 30% to about 50%, and made the particle size distribution more uniform, reducing the average particle size from 54.84nm to 39.9nm. When applied as a thin film on the top of silicon solar cells, the modified  $\text{Cs}_4\text{PbBr}_6$  nanoparticles significantly enhanced the external quantum efficiency (EQE) of the solar cells compared to the unmodified particles, which may indirectly improve the heat accumulation problem by increasing the absorption and conversion efficiency of photons.

Carbon dot (CD) and epoxy resin-based luminosity downshift (LDS) nanocomposites for solar cell encapsulation and laminating [11]. They used a cost-effective and environmentally friendly synthesis technique, creating carbon dots using a one-step microwave-assisted process that produced a 34% photoluminescence quantum yield. Using spin coating technology, these carbon dots were combined with epoxy to create a thin film that was subsequently placed to the silicon solar cells' surface. The findings demonstrated that this LDS nanocomposite could effectively transform high-energy UV photons into low-energy visible light, increasing the silicon solar cells' external quantum efficiency (EQE) and boosting power conversion efficiency by 1.65%. Furthermore, this nanocomposite helped to lessen heat accumulation by greatly enhancing the stability of the solar cells under UV light.

Quantum dots (QDs) are considered to be potential spectral converters for photovoltaic (PV) devices due to their superior photoluminescence (PL) properties [12]. Two quantum dots were synthesized, CdZnS/ZnS core-shell quantum dots and inorganic encapsulated crystalline  $\text{CsPbBr}_3$  quantum dots [13]. They used a hot injection method to prepare these quantum dots and then cast them into thin films for application on a silicon photodetector surface. The CdZnS/ZnS core-shell quantum dots, with an average particle size of about 9nm, showed a significant absorption peak at 283nm and a corresponding emission peak at 469nm. In contrast, the  $\text{CsPbBr}_3$  quantum dots exhibited an absorption peak at 261nm and an emission peak at 521nm. Experimental results demonstrated that both quantum dots could effectively downshift high-energy photons to low-energy ones, thereby broadening the spectral response of the silicon photodetector. When used as nanocomposite films, the CdZnS/ZnS quantum dots showed better performance and stability than the  $\text{CsPbBr}_3$  quantum dots, with a higher spectral response and photoluminescence quantum yield. This suggests that CdZnS/ZnS quantum dots are more effective in practical applications for better photothermal management and reduced risk of heat accumulation.

### 2.3.3 Upconversion

Light conversion efficiency is limited by the near-infrared (NIR) region, which comprises 44% of the solar spectrum [14]. Designing nanocomposite films to up-convert NIR light can significantly boost solar cell efficiency and prevent heat accumulation. Annelise Kopp Alves et al. enhanced flexible perovskite solar cells' efficiency by adding an erbium-doped forsterite ( $\text{Mg}_2\text{SiO}_4: \text{Er}^{3+}$ ) up-conversion layer. They converted wasted near-infrared energy into visible light by depositing this layer on  $\text{TiO}_2$  electron transport layers using RF sputtering. Their method enhanced the open-circuit voltage from 1.05 V to 1.19 V, the short circuit current density from 22.1  $\text{mA}/\text{cm}^2$  to 23.1  $\text{mA}/\text{cm}^2$ , and the power conversion efficiency from 16.1% to 20.6%. Additionally, the cells demonstrated improved thermal and moisture durability, maintaining 75% of their initial efficiency after 500 hours in ambient conditions. This research provides a promising method to boost perovskite solar cells' efficiency and stability, advancing next-generation photovoltaic technology.

$\text{Tb}^{3+}$  and  $\text{Yb}^{3+}$  ions are doped into  $\text{Y}_2\text{O}_3$  nano-amorphous and covered with a salicylic acid-doped polyvinyl alcohol (PVA) polymer matrix to create TYY:SA/PVA composites, a novel manufacturing technique for luminous nanocomposites [15]. The material exhibited significantly enhanced green luminescence under UV, visible, and near-infrared (NIR) light excitation, with the green luminescence intensity of  $\text{Tb}^{3+}$  ions increasing by 19 times compared to uncoated TYY samples. The SA/PVA-coated nanophosphor blocked the quantum-cutting process from  $\text{Tb}^{3+}$  to  $\text{Yb}^{3+}$  ions, reducing the NIR luminescence intensity of  $\text{Yb}^{3+}$  ions. Additionally, under NIR excitation, both TYY: SA/PVA and TYY materials showed strong green luminescence emission from  $\text{Tb}^{3+}$  ions through cooperative energy transfer between two  $\text{Yb}^{3+}$  ions. The composite material improved the external quantum efficiency of solar cells by 3%-5% in the 400nm-1000nm range. I-V characteristic tests revealed that simultaneous excitation with UV, visible, and NIR light increased the photon density in the blue, green, and NIR regions, enhancing the light absorption of the photovoltaic cell. This research offers new ideas for developing brighter, high photon flux luminescent composite materials for use in luminescent solar collectors.

Nanocomposite films doped with different concentrations of  $\text{Ho}^{3+}$  ions were prepared by a modified sol-gel technique, spin-coated onto glass substrates and then annealed at 300°C and 500°C for 3 hours [16]. With crystallite diameters ranging from 15 to 20 nm and an average thickness of roughly 1.7  $\mu\text{m}$ , the films demonstrated good transparency, adhesion, and smoothness. An 808 nm laser diode was used to detect up-conversion emissions in blue, red, and green. The film doped with 0.4mol%  $\text{Ho}^{3+}$  ions showed the strongest emission intensity. The thin films prepared show potential for optical sensors, photonics, and high-efficiency solar cells. As the concentration of  $\text{Ho}^{3+}$  grew, the films' refractive index rose from 1.5181 to 1.6446, while crystallite sizes decreased. The study found that annealing temperature and ion concentration significantly affected the optical properties, with optimal conditions being 500°C annealing and 0.4mol%  $\text{Ho}^{3+}$  concentration. The up-conversion emission intensity increased with laser power, and the research provides an experimental basis for developing new materials for photonic and waveguide applications.

## 3. Conclusion

Nanocomposite films have shown significant potential in enhancing thermal control and improving the efficiency of solar photovoltaic cells. Through various mechanisms such as down-conversion, down-shifting, and up-conversion, these films effectively manipulate the solar spectrum to optimize the utilization of light energy and mitigate heat accumulation in PV panels. The incorporation of diverse nanomaterials, including quantum dots, perovskites, carbon dots, and rare-earth-doped materials, has demonstrated remarkable improvements in the performance and stability of solar cells. For instance, the application of CdZnS/ZnS core-shell quantum dots and CsPbBr<sub>3</sub> quantum dots has broadened the spectral response of silicon photodetectors, while the use of erbium-doped forsterite layers in perovskite solar cells has significantly boosted power conversion efficiency and thermal stability. Future research should focus on further optimizing the synthesis and deposition

techniques of these nanomaterials, exploring new materials with enhanced properties, and developing scalable manufacturing methods to facilitate the commercialization and widespread adoption of nanocomposite films in solar PV systems. By continuing to advance the development of nanocomposite films, the scientific community can contribute to more efficient, durable, and sustainable solar energy solutions, driving the transition towards a renewable energy-dominated future.

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