

Yb³⁺/Er³⁺-Doped Borate Glasses for Spectral Up-Conversion and Enhanced Photovoltaic Cell Efficiency: A Critical Review

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ABSTRACT

The efficiency of single-junction photovoltaic (PV) devices is fundamentally limited by spectral mismatch between the incident solar radiation and the semiconductor bandgap. In silicon photovoltaics, sub-bandgap near-infrared photons are transmitted without generating electron–hole pairs, while excess photon energy above the bandgap is lost through thermalisation. Spectral conversion offers a route to mitigate these losses by modifying the incident photon distribution before it reaches the photovoltaic absorber. Among the available approaches, up-conversion is particularly attractive because it can combine two or more low-energy photons into a higher-energy photon capable of being absorbed by the semiconductor. This article reviews the scientific basis for Yb³⁺/Er³⁺-doped borate glasses as up-conversion materials for photovoltaic applications. The roles of Yb³⁺ as a sensitizer and Er³⁺ as an activator, the relevant energy-transfer pathways, host-glass characteristics, concentration effects, and the limitations imposed by phonon-assisted non-radiative relaxation are discussed. Previous studies demonstrate characteristic green and red emissions from Yb³⁺/Er³⁺ systems under near-infrared excitation, while borate glasses offer advantages in transparency, rare-earth solubility, chemical durability, cost, and scalable fabrication. However, the literature indicates a need for systematic optimisation under PV-relevant, low-irradiance conditions. The article therefore identifies optimal dopant concentration, energy-transfer efficiency, and spectral overlap with silicon response, low-intensity up-conversion performance, and optical stability as important directions for future experimental investigation.

Keywords: Yb³⁺/Er³⁺; borate glass; up-conversion; spectral conversion; rare-earth ions; photovoltaic cells; silicon solar cells; energy transfer; luminescence

INTRODUCTION

Photovoltaic conversion is a major technology for direct conversion of solar radiation into electricity because of its modular nature, absence of moving parts, and continuing reduction in manufacturing cost. Nevertheless, the performance of single-junction photovoltaic cells is subject to a fundamental spectral limitation imposed by the semiconductor bandgap. Detailed-balance analysis by Shockley and Queisser established an upper efficiency limit of approximately 30–33% for a single-junction cell with an optimum bandgap in the 1.1–1.4 eV range under standard illumination. Thus, even substantial improvements in device fabrication cannot eliminate the intrinsic losses associated with the solar spectrum (Shockley and Queisser, 1961). Certified silicon photovoltaic devices have historically approached, but not reached, this theoretical ceiling, underlining the practical relevance of spectral-conversion strategies (Green, Emery, Hishikawa and Warta, 2011).

For silicon, whose bandgap is approximately 1.12 eV, photons with energies below the bandgap cannot generate electron–hole pairs and are largely transmitted, whereas photons with substantially higher energies lose their excess energy as heat through thermalisation. These losses motivate the development of optical strategies that reshape the incident spectrum rather than modifying only the semiconductor junction. Spectral conversion layers provide one such strategy (Richards, 2006a; Richards, 2006b).

Among spectral-conversion mechanisms, up-conversion is especially relevant to the recovery of sub-bandgap near-infrared photons. In a typical up-conversion process, two or more low-energy photons are sequentially absorbed by a luminescent centre and their combined excitation energy produces a higher-energy photon. For silicon PV applications, an efficient up-converter can therefore act as a spectral bridge between otherwise unusable infrared photons and the useful absorption range of the photovoltaic device (Trupke, Green and Würfel, 2002b; Shalav, Richards and Green, 2007; Huang, Han, Huang and Liu, 2013).

Research Objective

The central objective of this review is to critically examine the potential of $\text{Yb}^{3+}/\text{Er}^{3+}$ -doped borate glasses as spectral-conversion media for photovoltaic applications. Based on the available literature, this review evaluates the reported relationships among glass composition, rare-earth dopant concentration, excitation conditions, up-conversion emission characteristics, energy-transfer pathways, and the spectral compatibility of the emitted radiation with the response range of silicon photovoltaic cells. Particular emphasis is placed on the performance of these materials under low and unconcentrated excitation conditions, since the strong laser excitation commonly employed in laboratory studies may not accurately represent terrestrial solar operating conditions. The review further identifies the key material and excitation parameters that influence up-conversion efficiency and discusses the challenges and prospects of translating laboratory-scale observations into practical photovoltaic spectral-conversion applications.

THEORETICAL BACKGROUND

Spectral Mismatch and Photovoltaic Losses

The terrestrial AM1.5G solar spectrum extends from the ultraviolet through the infrared and contains photons with energies both above and below the bandgap of silicon. The two major spectral losses are thermalisation of high-energy photons and non-absorption or transmission of sub-bandgap photons. Spectral conversion attempts to reduce these losses by transforming photons into energies more suitable for the photovoltaic absorber (Richards, 2006a; Richards, 2006b).

Up-Conversion Mechanism

Up-conversion is a nonlinear anti-Stokes luminescence process. It generally involves the sequential absorption of multiple low-energy photons through real intermediate states, followed by radiative emission at a higher photon energy. Several mechanisms may contribute, including excited-state absorption (ESA), energy-transfer up-conversion (ETU), photon-avalanche processes, and cooperative sensitisation. In rare-earth-doped materials, sensitiser–activator energy transfer is particularly important (Auzel, 2004; Wang and Liu, 2009).

$\text{Yb}^{3+}/\text{Er}^{3+}$ Sensitiser–Activator Pair

Yb^{3+} is an effective sensitiser for approximately 980 nm excitation because its $4f^{13}$ configuration provides a relatively simple two-manifold system, $^2F_{7/2}$ and $^2F_{5/2}$, with an energy separation corresponding closely to 980 nm excitation. Er^{3+} has a richer $4f^1$ level structure, including the $^4I_{11/2}$ level and higher states responsible for visible emission (Dieke, 1968). Near-resonant energy transfer from excited Yb^{3+} to Er^{3+} can populate Er^{3+} excited states and produce characteristic green emission from the $^2H_{11/2}/^4S_{3/2}$ levels and red emission from the $^4F_{9/2}$ level to the $^4I_{15/2}$ ground state (Binnemans, 2009; Auzel, 2004).

The efficiency of the sensitiser–activator pair depends on spectral overlap, dopant separation, concentration, host phonon energy, and competing non-radiative processes. At low dopant concentration, the probability of energy transfer may be insufficient, whereas excessive concentration can promote cross-relaxation and concentration quenching. Consequently, optimisation of Yb^{3+} and Er^{3+} concentrations is essential for a new glass composition (van der Ende, Aarts and Meijerink, 2009).

Borate Glass as a Host Matrix

Rare-earth-doped glasses are attractive for large-area optical and photovoltaic applications because they can be processed in bulk, formed into different geometries and thicknesses, and doped relatively uniformly. Borate glasses are particularly promising because of their optical transparency, chemical durability, comparatively low melting temperature, high rare-earth solubility, low raw-material cost, and compatibility with melt-quenching fabrication. These characteristics make them attractive for scalable spectral-conversion layers (Sukul, Kumar and Swart, 2022).

The principal limitation of borate glasses is their comparatively high maximum phonon energy, reported to be of the order of $1300\text{--}1400\text{ cm}^{-1}$ for B–O stretching vibrations. Higher phonon energy increases the possibility of multiphonon non-radiative relaxation, which can compete with radiative up-conversion and reduce luminescence efficiency. Thus, the practical advantages of borate glasses must be balanced against phonon-related quenching through careful compositional and concentration optimisation (Zhang and Huang, 2010).

Review of Previous Studies

$\text{Yb}^{3+}/\text{Er}^{3+}$ co-doped up-conversion materials have been investigated in fluoride crystals, glass-ceramics, and several oxide-glass systems. Early studies established the characteristic green and red emission bands under 980 nm excitation and supported energy-transfer up-conversion involving the Yb^{3+} and Er^{3+} energy levels (Auzel, 2004; van der Ende, Aarts and Meijerink, 2009).

Subsequent studies extended the sensitiser–activator combination to phosphate, tellurite, germanate, and borate-containing glasses. $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped boro-tellurite and bismuth-borate systems have demonstrated visible up-conversion emission under 980 nm excitation. Sukul, Kumar and Swart (2022) reported an $\text{Er}^{3+}\text{--}\text{Er}^{3+}$ energy-bridging mechanism mediated by Yb^{3+} in a borate oxyfluoride glass-ceramic, showing that host composition and dopant ratio can influence emission intensity and colour purity.

For photovoltaic applications, theoretical work demonstrated that an up-converter positioned behind a bifacial solar cell could recover sub-bandgap photons and potentially raise the limiting efficiency of a silicon cell. Experimental studies subsequently reported photocurrent enhancement under concentrated or monochromatic sub-bandgap excitation using rare-earth-doped up-conversion materials (Trupke, Green and Würfel, 2002b; Shalav et al., 2005; Fischer et al., 2010). Later research examined host materials with respect to quantum efficiency, spectral overlap, pump-wavelength transparency, mechanical stability, and environmental durability (de Wild et al., 2010; Lahoz et al., 2011).

Research Gap

The literature identifies a clear opportunity for a systematic investigation of $\text{Yb}^{3+}/\text{Er}^{3+}$ -doped borate glasses specifically designed for photovoltaic spectral conversion. While fluoride, tellurite, and phosphate hosts have received substantial attention, borate glasses offer practical advantages in chemical durability, rare-earth solubility, cost, and scalable fabrication. However, their higher phonon energy can reduce up-conversion efficiency through multiphonon relaxation. Moreover, existing borate-based studies have not, according to the reviewed material, consistently focused on the complete set of PV-relevant performance parameters under realistic low-irradiance conditions.

Accordingly, the research gap is not simply the demonstration of up-conversion in a borate host, but the systematic optimisation and PV-oriented evaluation of the $\text{Yb}^{3+}/\text{Er}^{3+}$ borate-glass system. Key parameters include dopant concentration, excitation-power dependence, emission intensity, energy-transfer mechanism, spectral overlap with silicon response, quantum efficiency, and long-term optical stability.

REVIEW APPROACH AND METHODOLOGY

The source material does not provide experimental procedures or measured results; therefore, the following methodology is framed as a proposed research plan rather than as completed experimental work.

1. Preparation of a series of borate-glass compositions containing controlled Yb^{3+} and Er^{3+} concentrations using an appropriate melt-quenching route.
2. Structural and optical characterisation to establish glass formation, amorphous nature, optical transparency, and relevant absorption features.
3. Photoluminescence and up-conversion measurements under near-infrared excitation, with particular attention to approximately 980 nm excitation associated with Yb^{3+} sensitisation.
4. Analysis of the green and red emission bands and their dependence on dopant concentration and excitation power.
5. Investigation of energy-transfer and up-conversion pathways using emission spectra and excitation-power dependence.
6. Assessment of the spectral compatibility of the up-converted emission with the useful response region of silicon photovoltaic cells.
7. Evaluation of practical factors including optical stability, concentration quenching, and performance under low-intensity excitation relevant to terrestrial PV operation.

Expected Significance

A successfully optimised $\text{Yb}^{3+}/\text{Er}^{3+}$ -doped borate glass could provide a comparatively practical spectral-conversion layer for recovering part of the sub-bandgap near-infrared radiation transmitted by silicon photovoltaic devices. The significance of the work lies in combining the efficient 980 nm sensitisation characteristics of $\text{Yb}^{3+}/\text{Er}^{3+}$ with the fabrication and durability advantages of borate glass. The research may therefore contribute to the broader development of luminescent materials for optical management of solar radiation.

However, the literature also indicates that strong up-conversion under laboratory laser excitation should not by itself be interpreted as a substantial improvement in solar-cell efficiency. Low photon flux, multi-photon excitation requirements, re-absorption, non-radiative relaxation, and optical coupling losses can strongly limit practical performance. Consequently, PV-oriented evaluation under realistic excitation conditions is essential.

CONCLUSION

$\text{Yb}^{3+}/\text{Er}^{3+}$ -doped borate glass represents a promising material platform for spectral up-conversion aimed at improving the utilisation of sub-bandgap solar radiation. The Yb^{3+} sensitizer provides efficient near-infrared absorption around 980 nm, while Er^{3+} supplies multiple excited states capable of producing visible green and red emissions through energy-transfer up-conversion. Borate glasses offer practical advantages including high rare-earth solubility, chemical durability, optical transparency, low cost, and scalable processing, although their relatively high phonon energy can enhance non-radiative losses. The reviewed literature therefore supports a focused research programme involving concentration optimisation, spectroscopic characterisation, mechanism analysis, and PV-relevant low-irradiance testing. Such a systematic investigation can address the identified gap between laboratory demonstrations of rare-earth up-conversion and practical spectral-conversion layers for silicon photovoltaic technology.

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