PhD Thesis Defense: Photonic Strategies for Approaching Fundamental Limits in Thermophotovoltaic Energy Conversion

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Thermophotovoltaic (TPV) systems convert thermal radiation into electricity by coupling a hot emitter to a photovoltaic (PV) cell. Despite important recent developments in the field, TPV performance is ultimately constrained by a persistent power--efficiency trade-off: broadband radiative exchange between an emitter and a cell yields high electrical power at the expense of efficiency, whereas narrowband exchange leads to high efficiency at the cost of reduced power. A more empirical way to express this constraint is the difficulty of improving both the current and voltage characteristics of a cell simultaneously.

Understanding the power--efficiency trade-off is therefore fundamental to optimizing TPV performance. This thesis develops a unified framework for understanding this trade-off and identifying photonic and electronic design strategies that enable optimal operation while remaining anchored to thermodynamic bounds.

The first part of the thesis establishes the conceptual and quantitative backbone. A photonic view of thermal radiation connects Planck's law and the Stefan--Boltzmann limit to the density of optical states, coherence, and surface polaritons, and clarifies the distinction between far-field and near-field exchange. These ideas are combined with the practical building blocks of TPVs - spectral and angular emission control, junction physics, recombination, and quantum efficiency - to establish a practical design toolkit for TPVs. Within this toolkit, detailed-balance and radiative--thermodynamic analyses place TPVs on a power--efficiency landscape bounded by Carnot and exergy (Landsberg) limits and identify spectral bandwidth as a central control knob governing performance.

On this foundation, the thesis explores three routes for mitigating the trade-off. First, hot-carrier TPVs introduce an internal thermodynamic degree of freedom by treating the carrier subsystem as a reservoir with its own temperature and chemical potential and by harvesting carriers through energy-selective contacts; in the ideal radiative limit, this enables a single junction to emulate multicolor performance and approach Carnot efficiency at finite power. Second, an analytical framework for a near-field TPV system based on fluctuational electrodynamics derives analytical expressions for photon tunnelling between plasmonic and semiconducting media, establishing scaling laws that show how evanescent modes can deliver super-Planckian, spectrally concentrated fluxes that support high power and high efficiency simultaneously. Third, substrate engineering is shown to be instrumental in near-field TPV design: in an ITO/InAs case study, optimizing thin, low-loss plasmonic films with tuned plasma frequency and thickness reshapes the tunnelling spectrum, concentrating useful above-bandgap transfer while suppressing sub-bandgap losses, and shifts electrical power-efficiency curves outward in the radiative limit.

This thesis reframes the TPV power--efficiency compromise as malleable rather than fixed: while the global thermodynamic frontiers are immutable, the effective frontier accessible to practical architectures can be steered through controlled interventions in spectra, modes, and carrier energetics. The analytical models, thermodynamic benchmarks, and optimization strategies developed here provide a principled basis for designing and evaluating TPV systems that combine photonic control, hot-carrier extraction, and near-field coupling, and for assessing these theoretical results in relation to realistic material and device constraints.

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