

Laser-Etched Black Metal Surfaces for Ultra-Efficient Solar Thermoelectric Generators

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ABSTRACT

Solar thermoelectric generators (STEGs) convert sunlight to electricity via the Seebeck effect but have been limited by low temperature gradients and poor absorber/heat-sink management. Recent work demonstrates that femtosecond (fs) laser-etched “black metal” selective solar absorbers and laser-textured micro-structured heat dissipators substantially improve optical absorption and thermal management, enabling up to a 15× increase in STEG power output with modest weight penalty. Key advances are (1) creation of tungsten-based selective solar absorbers (W-SSA) with >80% solar absorptance and reduced IR emissivity, (2) encapsulation/greenhouse thermal management that cuts convective losses by >40%, and (3) laser-textured aluminum μ -dissipators that double cold-side cooling capacity — together producing far higher ΔT across TE modules and dramatically higher harvested power. This paper reviews the material- and device-level mechanisms, summarizes experimentally observed performance gains, presents comparative data, and discusses scalability and application prospects.

Keywords: *Solar thermoelectric generator, femtosecond laser, black metal, selective solar absorber, thermal management, tungsten, microstructured heat sink*

INTRODUCTION

Thermoelectric generators (TEGs) generate voltage from a temperature difference and, when driven by sunlight, form STEGs. Historically, STEGs suffered low conversion efficiencies (often <1% under non-concentrated sunlight) because of limited ΔT across TE legs and thermal losses at the absorber and sink. Improving optical absorption of the hot side while minimizing IR re-emission and simultaneously enhancing cold-side dissipation are two complementary strategies to raise ΔT and delivered electrical power. Recent demonstrations show that fs-laser surface engineering of metals produces selective solar absorbers and high-performance micro-structured heat sinks that together enable large STEG performance gains.

Background: femtosecond-laser blackening & spectral engineering

Ultrashort-pulse (femtosecond) laser irradiation produces dense nano-/micro-structures (LIPSS and related features) on metal surfaces; these structures, and any laser-induced oxides, alter plasmonic and scattering behavior to produce broadband or selective absorbers. By tuning fluence, pulse number, and scan speed, laser processing can be directed to create either broadband blackening or spectrally selective absorbers that absorb strongly across the solar band ($\approx 300\text{--}2500$ nm) while exhibiting lower emissivity in IR thermal wavelengths. Early and foundational demonstrations established that fs-laser-treated tungsten, copper and aluminum can act as durable absorbers and, when protected with thin dielectric films (e.g., TiO_2), can sustain elevated temperatures.

MATERIALS & METHODS (REPRESENTATIVE EXPERIMENTAL STRATEGY)

Hot side (W-SSA): bulk tungsten discs are processed with a Ti:sapphire fs laser (typical: 800 nm central wavelength, ~ 30 fs pulses, kHz rep. rate) using parameter sets that favour selective-absorber morphologies (lower fluence, higher scan speed) to produce dense but small nanostructures. A conformal dielectric overcoat (~ 200 nm TiO_2) is deposited to stabilize the nanostructures at high temperature.

Cold side (μ -dissipator): aluminum plates are laser-machined into hierarchical micro-finned or porous microstructures that increase convective surface area and enhance radiative cooling. The microstructured heat sink is optimized for low mass and high cooling capacity (reported $\sim 2\times$ improvement vs. untreated Al in recent work). Thermal coupling to TE modules uses standard thermal interface materials.

Thermal management: lightweight greenhouse enclosure (transparent window) reduces convective loss around the hot absorber; combined with selective absorber properties and enhanced cold sinking, ΔT across TE modules is maximized. Performance measured under concentrated and non-concentrated illumination with electrical output recorded across load sweeps.

RESULTS

Table: 1

Property / Metric	Untreated (reference)	Laser-engineered (representative)	Reported change
Solar absorptance (hot side)	moderate (metallic reflectance)	>80% for W-SSA.	Strong increase.
IR emissivity (hot side)	higher radiative loss	Selective spectral profile → lower mid-IR emissivity	Reduced radiative loss.
Convective loss (with greenhouse)	baseline	>40% reduction (greenhouse coupling)	Lower heat loss.
Cold-side cooling (μ -dissipator)	baseline Al heat sink	~2× cooling capacity vs. untreated Al	Improved T_c lowering.
ΔT across TE module	low	substantially increased	Higher open-circuit Seebeck and power.
STEG output power	≤ baseline (typically low)	~15× increase (with combined spectral + thermal management)	Major performance gain.

DISCUSSION

Mechanisms of improvement

The performance gains follow from two linked mechanisms: (1) spectral control — fs-laser patterning produces plasmonically active nano/microstructures that trap and absorb incident solar photons efficiently across the solar band while minimizing absorption/emission at thermal IR wavelengths; and (2) thermal management — reducing convective losses around

the hot absorber and boosting cold-side heat removal both increase ΔT across thermoelectric legs, which often dominate STEG output. The combined approach leverages device-level engineering rather than requiring breakthroughs in TE material ZT, making it immediately attractive for near-term application.

Practical considerations & robustness

Laser-induced nanostructures can oxidize or change morphology at high temperatures, degrading spectral performance; the community has shown that thin dielectric passivation (e.g., TiO_2) or protective coatings can maintain absorber function at elevated temperatures (e.g., up to hundreds of $^\circ\text{C}$) and during annealing cycles. Laser processing is additive-free and maskless, which helps scalability, but throughput and equipment cost (fs lasers, precision stages, vacuum/coating systems) are factors to consider for large-area deployment.

Applications & outlook

Because the approach increases power per unit mass (high power-density), immediate applications include remote wireless sensor networks, wearables with moderate power needs, and distributed off-grid sensors. While STEGs remain unlikely to replace PV farms for bulk electricity, the large relative gains make STEGs attractive where reliability, low maintenance, durability, or specific form-factor constraints matter. Ongoing research aims to (a) scale laser texturing to large panels (nonlinear/parallel laser approaches), (b) refine protective coatings for long-term durability, and (c) combine absorber engineering with next-generation TE materials and radiative-cooling strategies for further gains.

CONCLUSION

Femtosecond-laser spectral engineering produces black/selective metal absorbers that — when combined with clever, lightweight thermal management (greenhouse enclosures) and laser-textured μ -dissipators — dramatically increase STEG output (recent demonstrations report up to $15\times$ improvement). This device-level pathway sidesteps the slow progress in TE material ZT improvements and opens realistic near-term applications for STEGs in niche, high-value, or constrained environments. Future work should emphasize large-area manufacturing, long-term stability under environmental exposure, and integration with optimized TE modules and radiative cooling schemes.

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