WHITE PAPER

Thermoelectric Cooling in Photonics: Applications and Benefits

July 2025

sheetak
Advanced Thermoelectrics

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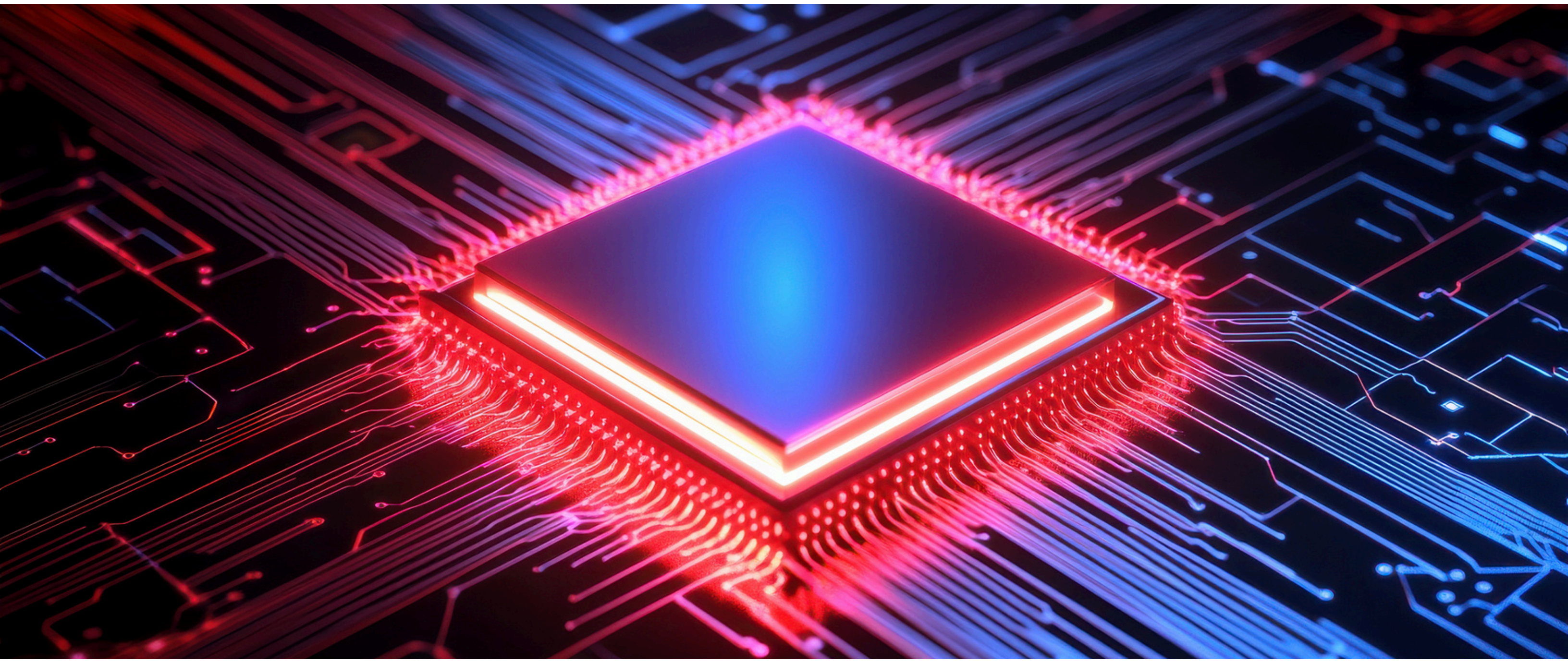
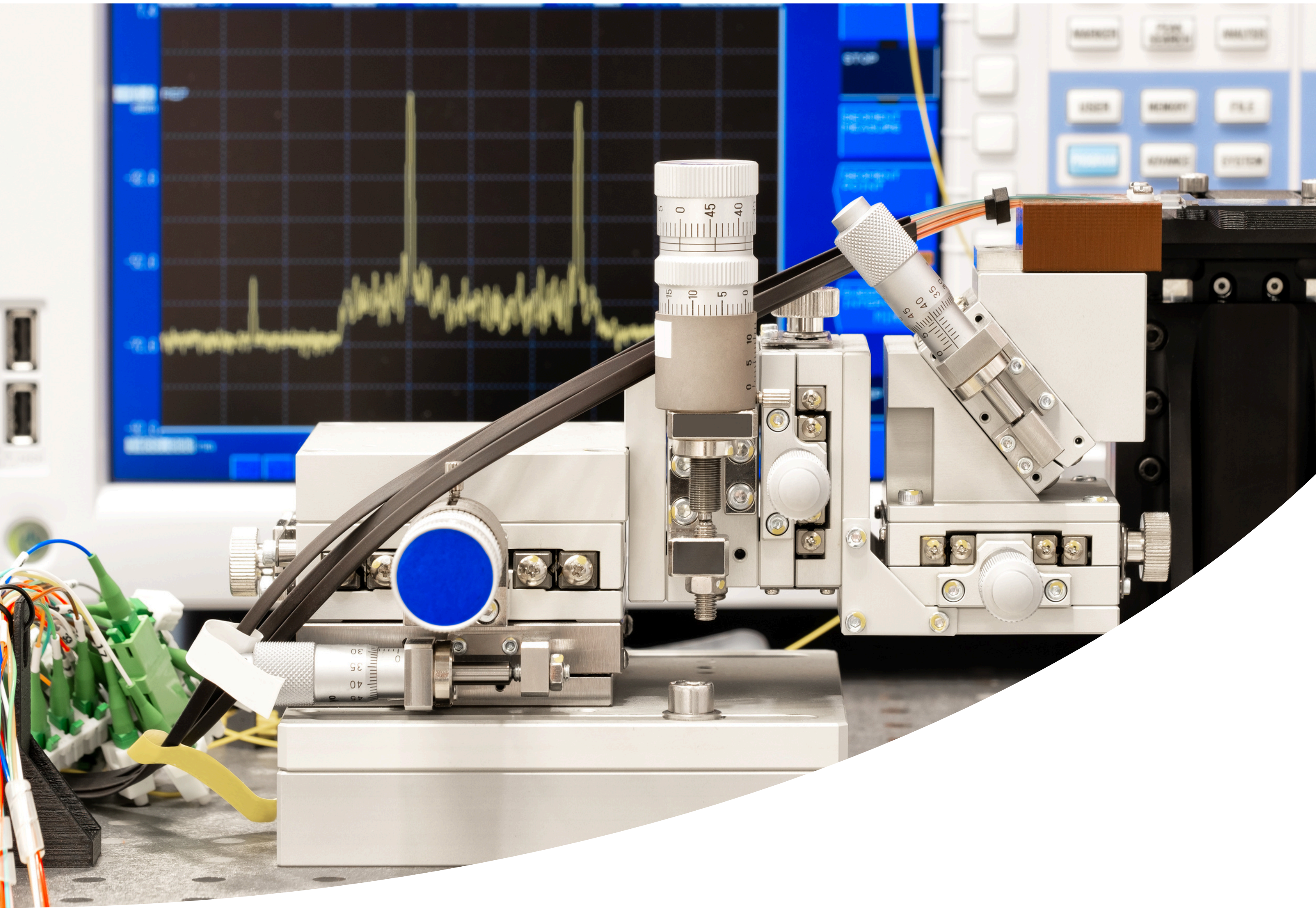




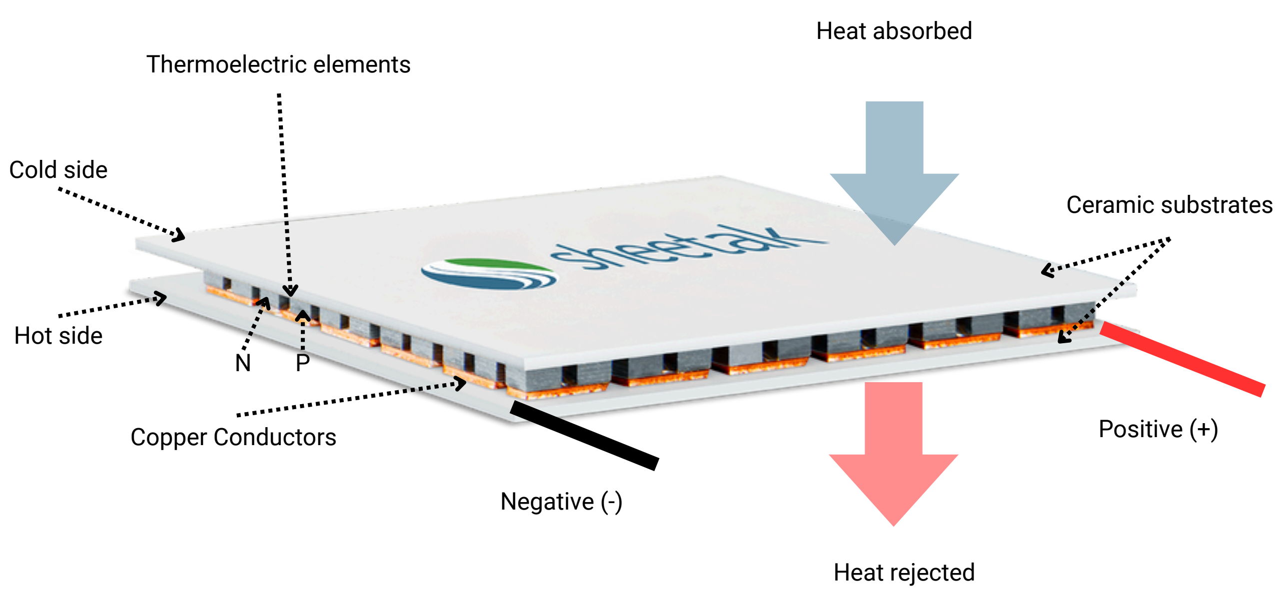
Executive Summary

As photonics systems advance toward higher performance and miniaturization, the challenge of thermal management becomes a limiting factor in device reliability and performance. This white paper presents a comprehensive analysis of thermoelectric coolers (TECs) in photonics, focusing on their role in precision thermal regulation. We discuss the fundamental physics underlying TEC operation, the selection and behavior of thermoelectric materials, and performance-critical metrics such as power input, coefficient of performance (COP), and achievable temperature differential (ΔT). We also explore real-world implementations across laser cooling, co-packaged optics, silicon photonics, pump lasers, and transceivers. Sheetak's CENTUM® thermoelectric coolers are integrated into these use-cases to highlight their advantages and performance in photonics applications.

Introduction to Thermoelectric Coolers *(TECs)*

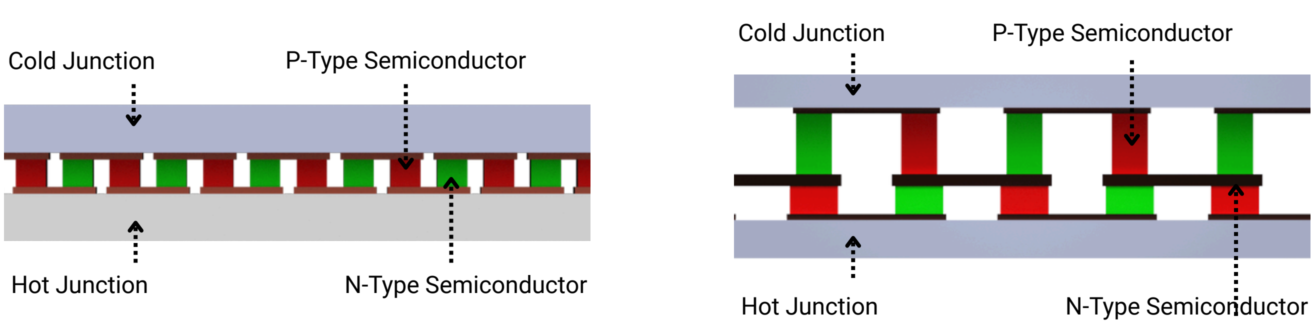
TECs exploit the Peltier effect, wherein a voltage applied across dissimilar semiconductors induces heat transfer from one junction to another. Each TEC module consists of a series of thermocouples, pairs of n-type and p-type semiconductor elements, connected electrically in series and thermally in parallel. When current flows, heat is absorbed at the cold side and expelled at the hot side, establishing a temperature gradient.

Figure 1.1



TECs provide solid-state, vibration-free, and highly precise thermal management solutions. Sheetak's TECs are built with advanced bismuth telluride (Bi_2Te_3) compounds, optimized doping concentrations, and fine-pitched ceramic substrates for superior heat spreading.

Figures 1.2 and 1.3



TECs in the Photonics World

Photonics components are extremely sensitive to temperature variations, which can shift emission wavelengths, degrade signal quality, and lead to premature component failure. For example, in laser diodes, a temperature change of just 1°C can shift the emission wavelength by approximately 0.3 nm, enough to cause misalignment in DWDM systems.

With increasing power densities and packaging complexity, TECs are essential for:

- Maintaining wavelength stability in DFB/DBR lasers.

Figure 2.1

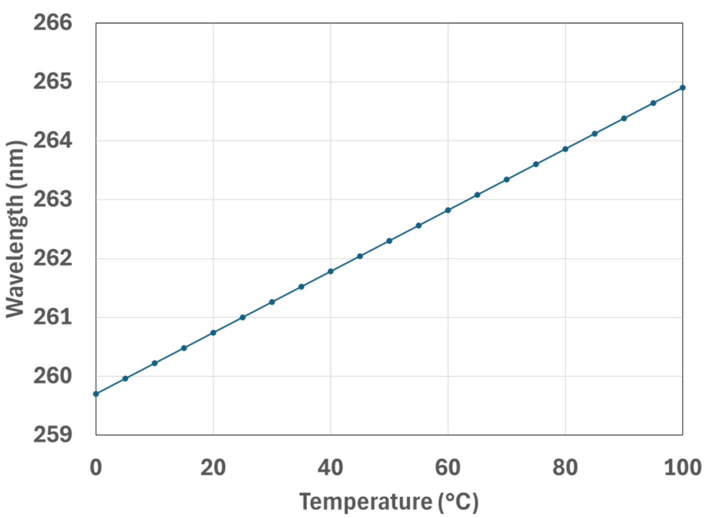
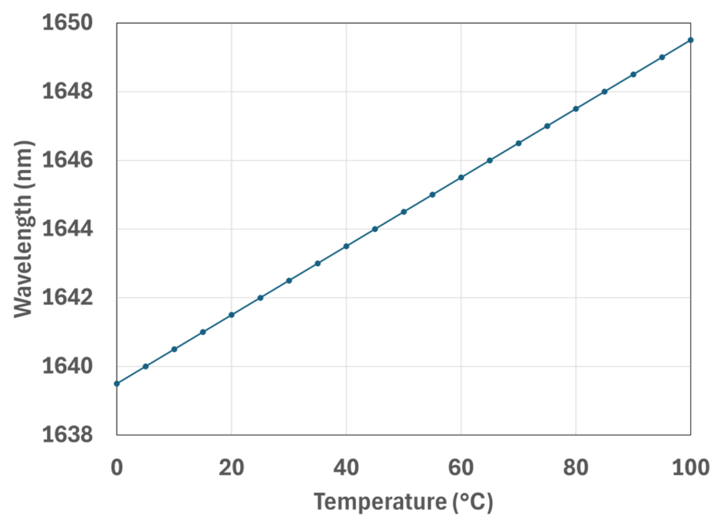


Figure 2.2



- Reducing phase noise and jitter in high-speed modulators.
- Improving quantum efficiency in photodetectors.
- Enabling longer mean time between failures (MTBF) in mission-critical systems.

Key Applications and Use Cases of TECs

Laser Cooling

Laser diodes operate efficiently within narrow temperature bands (typically ±0.1°C). Deviations impact wavelength, power output, and lifetime. TECs manage ΔT values often exceeding 50°C, counteracting self-heating during continuous-wave operation.

- Physics insight: TECs maintain the active region below its thermal rollover point, thereby avoiding mode-hopping and ensuring beam coherence.
- Materials: High-ZT Bi_2Te_3 is used due to its low thermal conductivity and high Seebeck coefficient.
- Design consideration: Heat sinks or active heat extraction must accompany TECs to dissipate hot-side heat efficiently.

High-power laser systems demand precise temperature control to maintain beam quality and stability. Sheetak's CENTUM® TECs, with their multi-stage architecture, offer exceptional temperature differentials (ΔT_{max} up to 110°C) and cooling capacities (Q_{max} up to 42W), ensuring optimal laser diode performance and longevity.

Imaging Sensors

Modern CMOS (Complementary Metal-Oxide-Semiconductor) and InGaAs (Indium Gallium Arsenide) imaging arrays such as industrial machine-vision and SWIR cameras suffer performance loss from thermally-induced dark current and hot pixels.

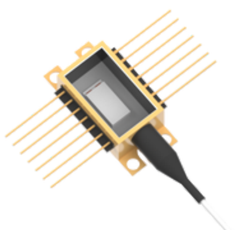
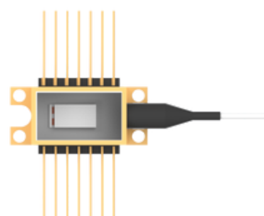
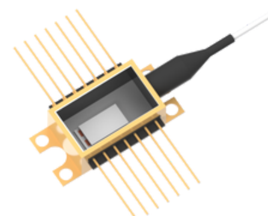
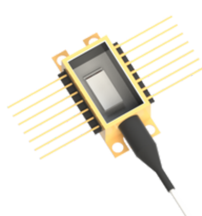
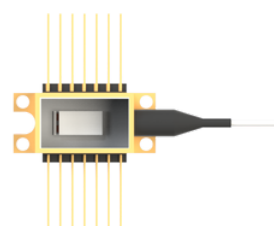
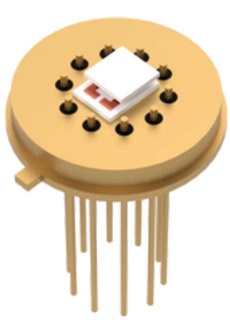
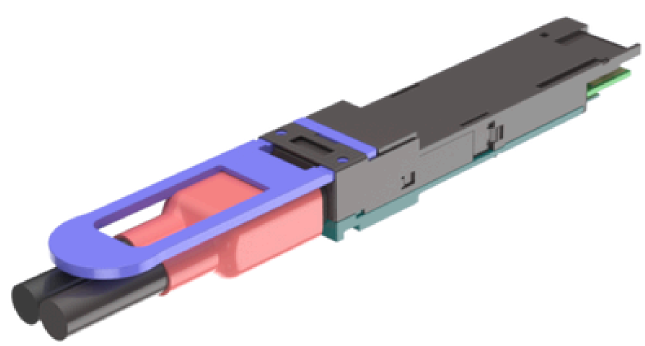
- Dark-current suppression: Every 6°C drop halves dark current; TECs routinely hold sensors at −20°C to −40°C without cryogens.
- Sensor uniformity: Lower temperature staves off thermal random telegraph noise, improving SNR and enabling longer exposure times.

Package integration: Sheetak micro-TECs are as small as 3 x 3mm and can mount directly under the sensor die, adding <0.5 g mass which is ideal for UAVs and mobile diagnostics.

Pump Lasers and Optical Transceivers

These are the heart of optical amplifiers and transmission systems, where operating temperature dictates power output and frequency precision. Pump lasers and optical transceivers are vital in communication systems, where temperature fluctuations can impact efficiency. The high ΔT_{max} and customizable configurations of CENTUM® TECs make them ideal for maintaining optimal operating temperatures, enhancing the performance and reliability of these components.

- Design target: Maintain junction temperature around 25°C even when enclosure or ambient reaches 60–80°C.
- Engineering focus: Selecting TECs with optimal Q_{max} and ΔT_{max} values ensures stable operation over extended temperature ranges.

Silicon Photonics

Silicon photonics (SiPH) devices are sensitive to temperature variations, which can affect signal integrity. CENTUM® TECs offer precise thermal control, stabilizing the operating temperature of silicon photonics chips and ensuring consistent performance even under varying environmental conditions.

Silicon photonic devices leverage passive waveguides and active III-V gain sections integrated via bonding.

- Thermal issue: Thermo-optic coefficient of silicon (~1.86 x 10^{-4}/°C) makes phase shifters and modulators highly temperature sensitive.

- TECs function: Actively stabilize chip temperatures to maintain phase integrity and minimize wavelength drift.

- Important note: Optical crosstalk and insertion loss can worsen with temperature; TECs ensure circuit-level predictability.

Co-Packaged Optics

In co-packaged optics (CPO), lasers sit millimeters from switch ASICs dissipating >25 W. Conventional 1-mm-pitch Bi_2Te_3 legs are often too bulky. Sheetak's forthcoming thin-film TECs are manufactured on 50µm Si carriers with leg pitches <100µm that shrink the cooling element footprint by more than fivefold while enabling localized, per-channel thermal control. A thin-film platform enables instant response time, potentially increasing SNR in these systems.

Our initial design aims for:

- ΔT_{max} over 50°C
- Cooling density >50 W cm^{-2}
- Seamless flip-chip bonding to the optics engine

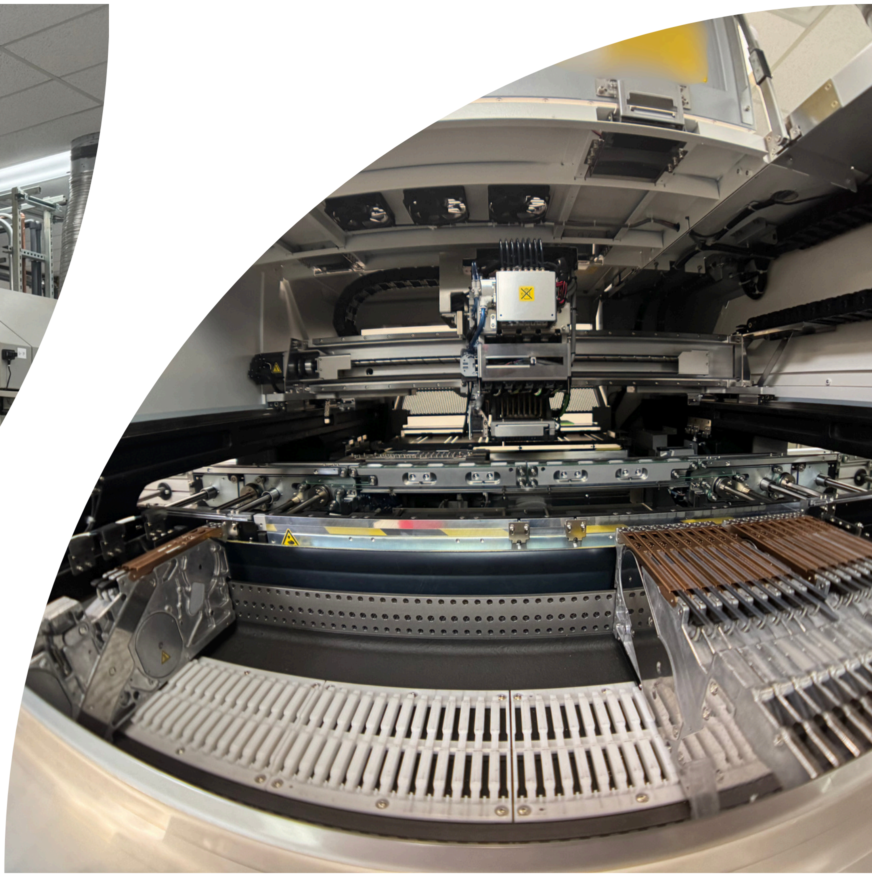
These thin-film TECs enable optical engines under 0.5 mm in height and pave the way for next-generation 1.6 T and 3.2 T CPO modules.

Thermoelectic Coolers: Technical Deep Dive

Manufacturing Process

Sheetak TECs are fabricated through a series of precise steps:

1. **Crystal growth** of Bi_2Te_3-based ingots under controlled conditions to maintain homogeneity.
2. **Doping** with Se, Sb, or Te to achieve optimal carrier concentrations.
3. **Micromachining** into thermoelectric pellets with dimensional precision.
4. **Solder bonding** to ceramic substrates (AlN/Al_2O_3) using SnSb or AuSn alloys, followed by electrical interconnection.
5. **Burn-in and cycle testing** to validate long-term thermal cycling performance.



Materials Used

- **n-type:** Bi_2Te_3 doped with Se
- **p-type:** Bi_2Te_3 doped with Sb
- **Substrates:** Aluminum Nitride (AlN), Alumina (Al_2O_3)
- **Interconnects:** Nickel or gold-plated copper
- **Solders:** SnSb or AuSn solders for high performance and reliability

Material performance is characterized by the figure of merit zT, where:

$$zT = \frac{S^2 \sigma T}{\kappa}$$

with:

- S = Seebeck coefficient
- σ = Electrical conductivity
- T = Absolute temperature
- k = Thermal conductivity

Sheetak targets zT values of ~1.2 at 300K for technological leap in the industry.

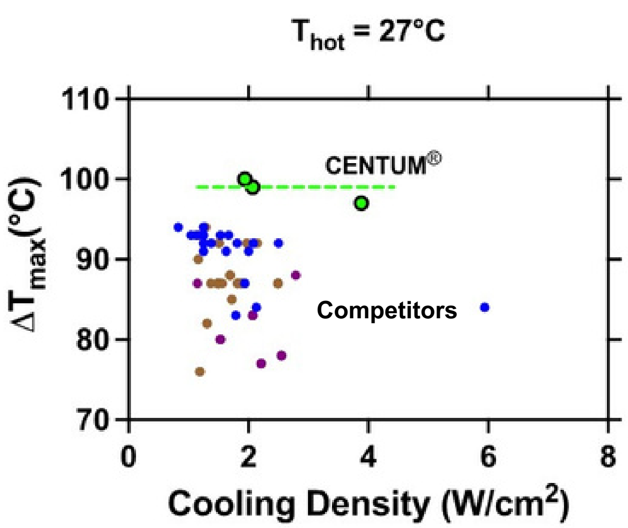
Form Factors

Modular customization is key. TEC arrays range from 3mm x 3mm micro-TECs to 40mm x 40mm multi-stage stacks, supporting vertical integration in photonics assemblies. Form factors are optimized using finite element thermal modeling for efficient integration into LD packages, TO-cans, or custom ASICs.

Performance Metrics

- **Power Consumption (P):** Depends on ΔT, ambient conditions, and thermal load (Q). P ∝ I^2R, where current (I) increases linearly with ΔT.
- **ΔT_{max}:** Sheetak TECs achieve ΔT up to 74°C in single-stage and >110°C in multi-stage configurations.
- **Q_{max}:** Sheetak High Cooling Power TECs > 200 W. Micro-TECs designed for Q < 1W in chip-level applications.
- **Coefficient of Performance (COP):** Ratio of cooling power to input power; typically ranges from 0.4–0.7 depending on operating point.
- **Thermal response time:** <1s for small TECs; important for systems requiring rapid temperature stabilization.

Figure 3.1



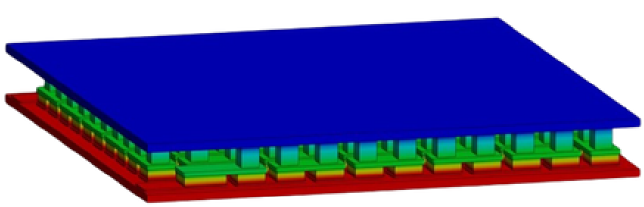
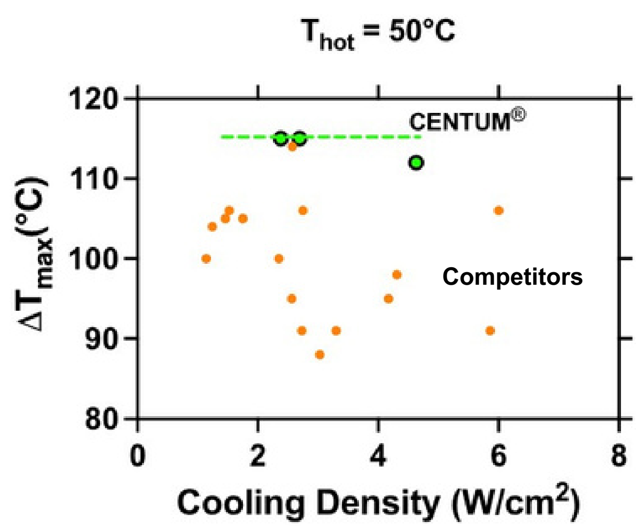
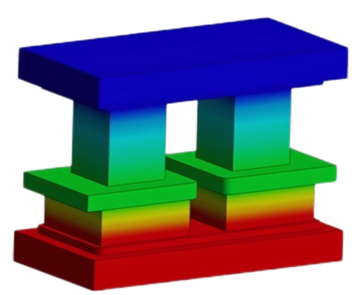


Figure 3.2





Case Studies and Real-World Applications

High-Power Fiber Lasers

A 2kW continuous-wave Yb-fiber laser exhibited spectral instability. By integrating Sheetak's dual-stage TEC with a water-cooled heatsink, diode temperature was stabilized within ±0.1°C, increasing spectral brightness and reducing failure rate by 40%.

Silicon Photonics in 400G Linear-drive Pluggable Optics (LPO) Transceivers

A Tier 1 telecom operator experienced phase drift in Mach-Zehnder modulators. Implementation of thin-profile TECs reduced drift, enabling longer link calibration intervals and boosting channel count per module by 30%.

SWIR Inspection Camera

3 x 3mm micro-TEC cooled sensor to −30°C, delivering four times lower dark noise and extending exposure window from 8ms to 25ms.

Co-Packaged Optics in Hyperscale Data Centers

Thermal crosstalk degraded optical links in a co-packaged 51.2T switch with integrated lasers. Adding Sheetak TECs with embedded thermistors allowed real-time thermal balancing via feedback control, improving module yield and reducing thermally induced bit errors.

Conclusion

Thermoelectric coolers are indispensable in advanced photonics systems, offering compact, precise, and highly controllable thermal solutions. Their utility spans from laser wavelength stabilization to photonic chip reliability enhancement. In the future, Sheetak's thin-film TEC platform will bring localized, flip-chip-compatible cooling to co-packaged optics and other ultra-dense photonic assemblies, sustaining bandwidth growth while maintaining system reliability.

As optical systems continue to scale in bandwidth and complexity, TECs will remain a cornerstone of system reliability, performance, and longevity.

References and Further Reading

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About Sheetak

Sheetak is redefining what's possible in thermal management and energy harvesting through advanced thermoelectric technology. With a portfolio of more than 25 issued patents, we design and manufacture high-performance thermoelectric chips that serve a diverse range of applications, from data centers and AI hyperscalers to telecom infrastructure, aerospace, and IoT systems.

Headquartered in Austin, Texas, Sheetak brings together deep expertise in material science, device engineering, and scalable manufacturing. By pushing the limits of thermoelectric performance, we help our customers meet today's toughest thermal challenges and enable the systems that power tomorrow.

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