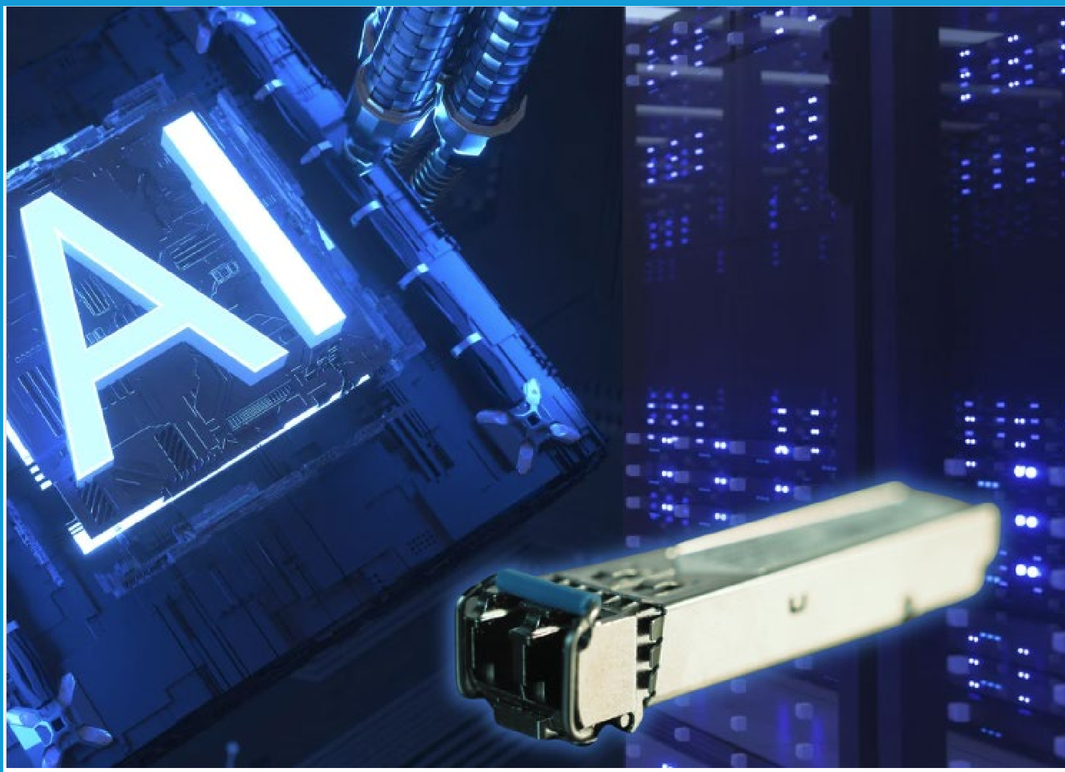

Optical Transceivers Cooling in the Age of AI Cluster Computers and Data Centers

Laird Thermal Systems Application Note

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Introduction

The rapid growth of artificial intelligence (AI) and large language models has led to a surge in demand for high-speed optical transceivers in data centers and AI cluster computers. With transceiver speeds scaling from 100 Gbps to 400 Gbps, and now moving to 800 Gbps, with the future roadmaps pointing toward 1.6 Tbps and beyond.to upcoming speeds of 1.6 Tbps, efficient thermal management is critical to ensure performance, reliability, and energy efficiency. This application note explores the latest developments in optical transceiver technology, focusing on their use in AI applications, their cooling requirements, and the customized thermoelectric cooling solutions being developed.

Optical Transceivers: Powering AI Communication

Optical transceivers enable high-speed communication between servers and network devices and are the critical components that facilitate the high-speed data transfer required for AI computations in modern data centers and AI cluster computers. As demand for AI cloud computing and data-driven demand increase, higher data transfer rates along with energy consumption are being pushed to unprecedented levels. As a result, the optical transceiver market has seen significant advancements in speed and efficiency and with it, the need for energy efficient cooling solutions in smaller form factors. The current and future transceiver speeds listed below represent the rapid progression from 100Gbps to 1.6Tbps transceivers as a result of these AI and data center applications.

- 100 Gigabit (100G) transceivers (used for entry-level data center applications)
- 400 Gigabit (400G) transceivers (widely used in current AI clusters)
- 800 Gigabit (800G) transceivers (currently preferred in high-demand applications)
- 1.6 Terabit (1.6T) transceivers (emerging technology supporting next generation AI workloads)

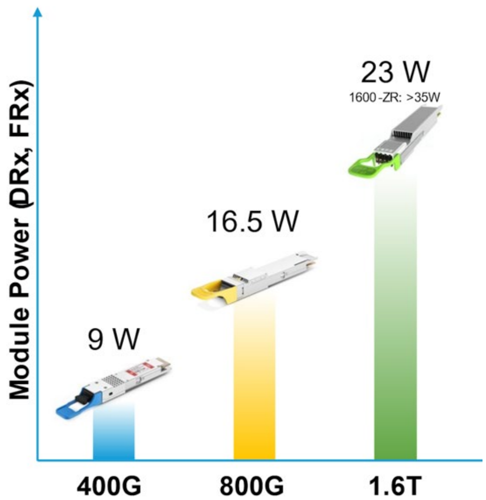
Pluggable optical transceivers rely on laser diodes for data transmission. The laser diodes emit a beam of light at a specific wavelength that is coupled into a fiber optic cable to provide high-speed data transmission over short to long distances. These lasers are sensitive to temperature variations, which can lead to signal degradation and reduced reliability. Consequently, precise thermal control is crucial for maintaining optimal performance. Thermoelectric coolers (TECs) provide reliable temperature stabilization by efficiently removing heat and maintaining a stable thermal environment, thereby improving signal integrity and extending the operating life of optical transceivers.

The recent AI boom has reinvigorated interest in optical transceiver technology, driving innovation and competition in the industry. Optical transceivers are categorized based on their transmission range:

TYPE	**RANGE**	**TECs Used for Cooling**
SR (Short Range)	Hundreds of meters	Typically not
DR (Data Center Range)	~500m - 2km	Typically not
FR (Front Range)	~2km - 10km	Occasionally
LR (Long Range)	~10km - 40km	Yes
ZR (Extended Range)	~40km - 100km	Yes

As the transmission distance increases, the need for temperature stabilization becomes more critical, leading to the use of thermoelectric coolers (TECs) in longer-range transceivers. Optical transceivers, especially those designed for longer ranges, require precise temperature control to maintain laser stability and performance.

Thermal Challenges in Optical Transceivers



Modern optical transceivers face an array of thermal challenges resulting from increasing module power requirements, coupled with size constraints that push these devices closer to their thermal limits. As data rates escalate from 400G to 3.2T and beyond, signal-to-noise ratio (SNR) budgets become ever tighter, magnifying the need for effective cooling and consistent temperature control. At the same time, energy efficiency has become a universal priority, driving power-saving solutions that extend throughout AI cluster computers and data centers.

Laser Diode Performance

The key component of the optical transceiver responsible for converting electrical signals into light is the laser diode. Although the transceiver itself faces many thermal constraints, it is ultimately the laser diode's ability to maintain stable performance—within strictly defined temperature ranges—that ensures the overall reliability of high-speed data links. The performance of a laser diode is influenced by many factors, including temperature, current, and optical power. Changes in temperature can cause changes in the electrical and optical properties of the laser diode, which can affect its performance. Operating at elevated temperatures continuously can also shorten the life span of the device.

The operating temperature of a laser varies depending on several factors, such as the type of laser and package, the power of the laser and the operating conditions. Standard lasers designed for telecom applications operate within a specific temperature range either C-temp band between 0 and 75C or I-temp band between -10°C and 85°C, although laser diodes in new optical devices can operate at even higher temperatures. Emerging telecom applications pursuing more than 400 Gb/s feature new optical devices and an expanded maximum temperature range.

At temperatures outside the maximum operating range, the performance of a laser diode can degrade due to increased thermal resistance and reduced current gain. This can result in decreased laser output power and increased threshold current. High temperatures can also shift the wavelength of a laser diode, impacting its performance and reliability. The shift in wavelength is caused by changes in the refractive index of the semiconductor material used in the laser diode. In some cases, a severe shift in wavelength can lead to significant crosstalk (interference), or even failure of the laser. For example, a distributed feedback (DFB) laser diode used in an optical communication application typically emits light at a wavelength of around 1260-1650 nm. An increase in temperature causes a shift in the peak wavelength (toward the long wavelength) of around 0.1 nm/°C.

At lower temperatures, the performance of a laser diode can improve due to reduced thermal resistance and increased current gain. This can result in increased laser output power and reduced threshold current. However, low temperatures outside the minimum operating range can also cause reduced photon life, increased recombination losses, and increased internal losses, which can offset the benefits of reduced thermal resistance.

Another problem attributed to fluctuations in temperature is that of crosstalk. This can be seen in communication links that require high bandwidth and long distances. Hyperscale data centers are an example of this with optical transceivers that use wavelength-division multiplexing to increase data throughput in optical fibers by combining multiple data streams in parallel. (IEEE Transactions on Components, Packaging and Manufacturing Technology, August 2022)

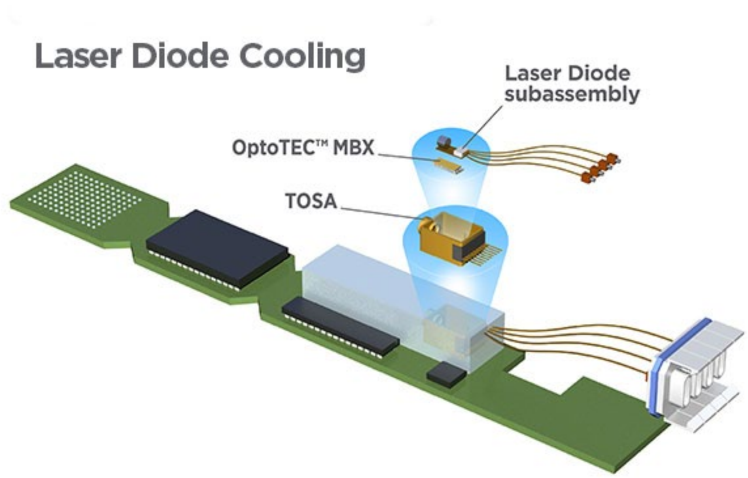
It is important to maintain a stable temperature of a laser diode to maintain a consistent wavelength, eliminating crosstalk and ensuring reliable performance. This can be achieved through temperature control systems that use thermoelectric cooling.

Laser Diode Cooling Challenges

Thermal management of laser diodes is more challenging than ever. More data is being transferred at higher speeds, power densities continue to increase, while product form factors continue to shrink. This inherently results in higher heat flux densities. The need for effective and efficient thermal management solutions is imperative to ensure the proper performance and longevity of laser diodes. In modern high-speed transceivers, multiple lasers (up to eight) may be placed on a single TEC to achieve the desired cooling. For example, an 800G transceiver might use eight lasers, each capable of 100 Gigabits per lane. Laird Thermal Systems focuses on customizing the thermoelectric element geometry and the number of couples based on the specific operating condition for each transceiver design. This customization allows for incremental improvements in efficiency, which is crucial to reduce overall power consumption in data centers and AI clusters.

Why Ultra-small or Micro TECs?

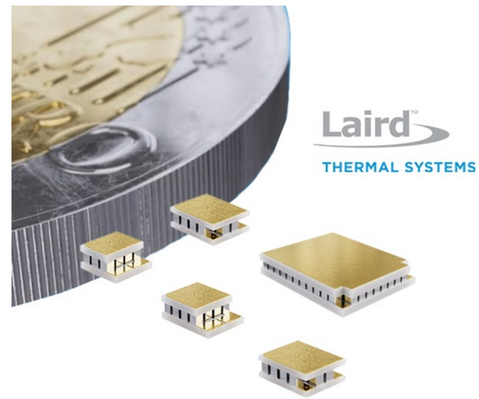
Advancements in laser diode technology also require advancements in thermal management solutions. As mentioned above, Laser diodes generate more heat as data throughput speeds increase and the distance between connection points increases. As a result, laser diode packages require higher heat pumping capacity to move heat away from sensitive electronics and out of the package. To pump the heat out, micro



TECs with higher packing fractions and thinner profiles are required to improve efficiency and maintain precise wavelength control and temperature stabilization.

New thermoelectric materials and high-precision manufacturing processes have enabled the development of micro TECs with lower profiles. This allows laser diodes to be made in smaller form factors without compromising thermal stability. They also respond more efficiently to changes in temperature, which is important for applications that require an efficient thermal control response, such as in optical communication systems. Higher efficiency can improve the laser diode performance and reliability enabling higher data transmission rates. In addition, micro TECs can be manufactured inexpensively with high throughput, which can help reduce the overall cost of the laser diode system.

The new **OptoTEC™ MBX** series from Laird Thermal Solutions is ideal for laser diode temperature stabilization. The ultra-miniature MBX series meets the requirements of modern laser diode applications including smaller size, lower power consumption, higher reliability, and lower cost in mass production. These factors can improve the performance and extend the reliability of the laser diode to enable innovation in next-generation telecom applications.



Engineered-to-Order Approach

As optical transceiver modules evolve—TEC suppliers are designing smaller, thinner, and shape-adaptable modules to fit these tight geometries without sacrificing performance. This includes micro-TECs for on-chip cooling of specific hotspots as an example.

Standard TECs can provide quick design results however top tier applications value engineered-to-order designs to optimize TEC to unique customer operating conditions and feature requirements. Highly customized, engineered-to-order solutions for optical transceiver cooling allow for TEC designs that have the lowest power consumption. The optimization process focuses on customizing the thermoelectric element geometry and number of couples based on the application operating condition of each transceiver design. This customization allows for incremental efficiency improvements, which is crucial for reducing overall power consumption in data centers and AI clusters.

Key Considerations in TEC Design

- **Low power consumption** is a priority due to the high density of transceivers in data centers
- **Sufficient cooling capacity** to handle the typical 1-to-3-watt range for optical transceivers
- **Compact form factor** to fit within the transceiver module while providing efficient cooling
- **High-volume manufacturability** for streamlined, scalable fabrication and assembly process to help reduce production costs and improve yield, ensuring TECs can be produced reliably and economically for large-scale deployments.

Application Example: 800Gbps Transceiver TECs

	SR	DR	FR	LR	ZR
Laser Type	VCSEL	CW LD	CW LD	EML	ITLA
Laser qty	8	4	4	8	1
Heat load	1.6 W	2.8 W	3 W	2.7 W	3.5 W
Model	MBX20,40,F2N,055039,GG	MBX18,72,F2A,068061,GG	MBX25,59,F2A,062052,GG	MBX18,67,F2A,092040,GG	MBX27,64,F2A,091043,GG

As AI continues to drive the demand for faster and more efficient data transfer, the optical transceiver market is expected to see continued growth and innovation. Customized thermoelectric cooling solutions will play a crucial role in enabling the performance and reliability of these critical components in the rapidly evolving landscape of AI and data center technologies.

Conclusion

The rapid advancement of AI and large language models has created a surge in demand for high-speed optical transceivers, particularly in data centers and AI cluster computers. As AI and data center applications continue to drive demand for faster and more efficient data transfer, the optical transceiver market is poised for continued growth and innovation. Advanced thermoelectric cooling solutions play a crucial role in enabling the performance and reliability of these critical components. By leveraging cutting-edge thermal management techniques, and optimized TEC designs, Laird Thermal Systems' customized thermoelectric cooling solutions play a crucial role in enabling the performance and reliability of these critical components.

By offering highly engineered, efficient cooling solutions with quick turnaround times, Laird Thermal Systems continues to be at the forefront of this dynamic and growing market. As the industry pushes towards even higher data transfer rates and greater power efficiency, the company's expertise in thermal management will remain a key enabler of next-generation optical transceiver technology.

More information on the OptoTEC™ MBX Series can be found by visiting https://lairdthermal.com/products/thermoelectric-cooler-modules/micro-MBX-series

About Laird Thermal Systems

Laird Thermal Systems develops thermal management solutions for demanding applications across global medical, industrial, transportation and telecommunications markets. We manufacture one of the most diverse product portfolios in the industry ranging from active thermoelectric coolers and assemblies to temperature controllers and liquid cooling systems. Our engineers use advanced thermal modeling and management techniques to solve complex heat and temperature control problems. By offering a broad range of design, prototyping and in-house testing capabilities, we partner closely with our customers across the entire product development lifecycle to reduce risk and accelerate their time-to-market. Our global manufacturing and support resources help customers maximize productivity, uptime, performance and product quality. Laird Thermal Systems is the optimum choice for standard or custom thermal solutions. Learn more by visiting www.lairdthermal.com

Contact Laird Thermal Systems

Have a question or need more information about Laird Thermal Systems? Please contact us at www.lairdthermal.com