

The Role of Optical Modules in Data Centers



Overview

This review paper analyzes optical technologies that will enable next-generation data center optical interconnects.

Key Takeaways

Optical modules are critical components in data centers, converting electrical signals into light for high-speed, low-latency, and long-distance data transmission, enabling efficient interconnectivity between servers, switches, and storage systems.

Function and Components

Optical modules serve as the bridge between electrical systems and optical fiber networks, converting electrical signals from servers or switches into optical signals for transmission over fiber, and vice versa at the receiving end . Each module typically contains a laser transmitter, a modulator to encode data onto light, and a photodetector to convert incoming optical signals back into electrical form . This process allows data to travel long distances with minimal loss, unlike copper cables, which suffer from resistance and signal degradation .

Types and Fiber Considerations



Optical modules come in various types and form factors, including SFP, QSFP-DD, OSFP, and emerging high-speed modules like 400G, 800G, and 1.6T . They can be fiber-based or copper-based, with fiber modules supporting single-mode (long-distance) or multimode (short-distance) transmission . Single-mode fibers are essential for cross-data center connections, while multimode fibers are suitable for intra-rack or short-range links .

Performance Advantages

Optical modules provide extreme bandwidth, ultra-low latency, and long reach, which are crucial for modern data centers handling AI, HPC, and cloud workloads . They enable high-density interconnects, allowing hundreds of ports in a single switch panel, and support protocols like RoCE and InfiniBand for high-speed GPU and storage communication . By minimizing latency and signal loss, optical modules ensure real-time data processing and efficient distributed computing .

Technological Evolution

Recent innovations include Linear Pluggable Optics (LPO), Linear Receive Optics (LRO), Co-Packaged Optics (CPO), and silicon photonics, which improve power efficiency, reduce heat, and increase data throughput . High-speed modules, such as 1.6T and 3.2T, require advanced cooling solutions due to power density and thermal crosstalk challenges . Industry adoption is accelerating, with companies deploying these modules in AI clusters and large-scale data centers to meet growing bandwidth demands .

Applications in Data Centers

Optical modules are indispensable for:

- Server-to-switch interconnects, enabling high-speed GPU cluster communication .
- Cross-data center links, supporting distributed AI model training and multi-site HPC workloads .
- Storage networks, ensuring high-speed data delivery and avoiding I/O bottlenecks .
- High-performance computing, where terabit-level bandwidth and low latency are critical for AI/ML training, scientific simulations, and big data analytics .

Conclusion

In modern data centers, optical modules are foundational to achieving high-speed, scalable, and energy-efficient connectivity. They enable the massive data flows required for AI, HPC, and cloud services, overcoming the physical limitations of copper cabling and supporting the evolution toward next-generation intelligent computing infrastructures .

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