All-Optical Switching: Past, Present and Future

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Abstract: Applications for all-optical switching have grown recently as performance, cost and reliability have matured. The technology is now poised for wide-scale deployment in both datacenter and telecom networks. © 2023 Richard Jensen
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1. Introduction

Using large matrix all-optical circuit switches (OCSs) to create a dynamic and flexible network fiber layer was a dream 25 years ago that is now becoming a reality to enable networks and datacenters to efficiently scale to meet the ever-increasing demand for bandwidth. All-optical circuit switches are unique in that they transfer traffic transparently from one optical fiber to another without converting the signals from optical to electrical and back to optical (OEO), as is done in an electronic packet switching fabric. The ability to switch all the traffic between fibers without regeneration allows low-cost and low-latency optical connections to create a flexible, dynamic physical fiber layer for networks and data centers. This virtualization of the fiber infrastructure enables new energy-efficient disaggregated architectures that can deliver new services faster and at lower cost by increasing equipment utilization and reducing the need to overbuild to meet peak traffic demands.

Large amounts of investment and engineering effort have gone into developing OCS technologies and applications over the last few decades [1-3]. Steady performance improvements and cost reductions over time have led to increasing deployments in a variety of diverse applications. For commercial success, many technological challenges needed to be overcome. These included matrix scalability, optical loss, switching speed, reliability and cost. The per-port cost has arguably been the greatest barrier to entry historically and the overall value proposition for all-optical switching relative to OEO switching increases greatly as the traffic data rates move to higher speeds and multiple wavelengths are combined on a single fiber. Reliability and resilience are also key factors to be considered in OCS design where the technologies are deployed in critical core network applications.

Optical switching has steadily overcome all these challenges and is already seeing large-scale deployments in some datacenter networks. In this paper, we will briefly cover the past, present and future trends in large radix OCS applications and illustrate how incremental improvements in OCS technology combined with advances in network control have led to new breakthrough applications.

2. Past History

The promise of optical switching was to provide low-cost, transparent flexible physical fiber network layer and significant research efforts to develop all-optical switching were well underway in the 1980s and 1990s. Large radix all-optical switches started to be commercially available around about 2003 with the development of beam-steering MEMS and piezoelectric switch cores. In the initial years, equipment suppliers, national laboratories, researchers and dozens of startup companies invested billions in a far-reaching array of optical technologies to develop all-optical switches. Many technologies were studied as part of the drive to develop large radix optical switches. Some notable technology examples have included: bubble jets in index matching fluid, dynamic holograms, planar lightwave circuits (PLCs), 2D- and 3D-MEMS, piezoelectric beam-steering and robotics [4].

Across technologies, initial costs were very high at up to $10K USD per fiber port, but reduced rapidly as production volumes increased. Optical losses were also high at 8-20dB optical loss per connection. These initial offerings generated interest across different industries and optical switching did see limited deployments in undersea transoceanic systems, testing, cyber security and other applications, but the high cost and optical losses limited wide-scale deployments. Costs reduced over time and performance improved but the economic turbulence from the market crash in the 2000s significantly reduced the ongoing investment in all-optical switching and added further barriers to deployment.

3. Present

Of all the technologies studied, four have stood the test of time to lead the commercial and research spaces: 3D-MEMS, Robotics, PLC and Piezoelectric. Of these, PLC technology is still primarily in the research phase, PLC technologies typically have smaller matrix sizes but can be arranged in multistage switch architectures to scale to build large radix OSCs. Steady performance improvements and cost reductions have increased the range of applications accessible to large OCSs. For larger switches, the cost per port has come down more than an order of magnitude per port and losses have dropped to the 1-3dB typical range expanding the available market for optical switching. Costs can still vary over a wide range depending on performance specs and sales volumes. The reliability of commercially available technologies has also been proven over time with billions of port hours of field deployments.

Today switches with matrix sizes in the 300x300 to 1,000x1,000 port range depending on the technology are commercially available. Innovation continues across all technologies. Recently, results were reported for a prototype 576x576 piezo-based OCS with median insertion loss of 1.4dB [5]. Overall, lower cost and higher reliability are seen as the main drivers for the large-scale deployment of optical switches.

A broad range of applications currently exploit OCS technologies, including cyber security monitoring, optical circuit protection and provisioning, Radio Frequency over Fiber (RFoF) systems, satellite uplinks, mobile fronthaul and broadcast video networks, system lab automation and manufacturing test, along with many other smaller markets.

Recent papers have clearly demonstrated the cost and performance benefits of OCS technology in datacenter network (DCN) architectures, in results published on the first large-scale OCS deployment in Google's Jupiter DCN [6,7]. Very large numbers of MEMS optical switches have been deployed over the last decade, replacing the spine layer of a spine-leaf DCN in an innovative disaggregated hybrid OCS/OEO packet architecture. Jupiter uses a Software-Defined Network (SDN) control plane for traffic engineering and to automate network operations for incremental capacity delivery and topology engineering. The OCS layer enables dynamic topology reconfiguration of the fiber connectivity to achieve 3x faster fabric reconfiguration compared with conventional OEO Clos architectures. Use of OCS technology has enabled Jupiter to deliver 5x higher speeds and capacity, 30% reduction in capex, 41% reduction in power consumption and 50x less downtime than the best-known alternatives [8].

4. Future Trends

The future for all-optical switching appears bright, with new applications and deployments on the horizon in datacenter, telecom and government networks. As OCS technology continues to evolve, we expect to see a wider range of applications along with higher numbers of switches deployed in both new and existing applications. In addition to new applications, there is also significant interest in developing optical switching technology to directly support alternative optical fiber types such as few-mode fiber, multicore fiber and hollow-core fiber [9]. While it is not possible to list all of the potential future applications in this summary paper, we will highlight some of the more interesting work.

Work continues on novel architectures using OCSs in RFoF applications including satellite uplink, broadcast production and secure government communications. As the transmission bandwidth increases, optical fibers and OCSs are a low-power, cost-effective alternative to bulky high-performance RF cables and RF switches. In 5G and 6G Mobile networks OCSs can be placed between Base Band Units (BBUs) and Remote Radio Heads (RRHs) to disaggregate and virtualize Cloud Radio Access Networks (C-RANs) increasing equipment utilization while improving overall service quality and availability. There is renewed interest in using OCS to provide Colorless, Directionless and Contentionless ROADMs for transport nodes [10,11]. All-optical switching also has applications in High-Performance Computing (HPC), space-based photonics [12] and quantum applications [13]. Ultra-low loss OCS elements are ideally suited for quantum key distribution, quantum computing and quantum networking applications where high optical transparency and minimal impairments are essential.

The most active research and development areas for OCS are in novel hybrid datacenter architectures to reduce costs, latency and to enable more efficient scaling to seamlessly interconnect large server groups. These efforts include work with Piezo, MEMs, Robotic and PLC technologies. PLC technology is still in the research phases but has significant potential for future applications [14]. There is significant focus on datacenter disaggregation using hybrid OCS and packet switches architectures to further leverage the combined power of a reconfigurable optical layer and SDN control. These efforts promise to reduce costs and energy usage further while enabling the ability to scale to meet future bandwidth demands [15,16].

5. Conclusion

High-radix optical circuit switches have now been commercially available for over 20 years and have enabled numerous applications wherever traffic needs to be routed between optical fibers, because of their transparency to data rate and format. Continuous improvements in cost, reliability and performance of OCS technologies are opening up new opportunities for broader applications. We are now seeing results of successful large-scale OCS deployment in data center networks and anticipate broader applications across datacenter, telecom and secure networks.

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