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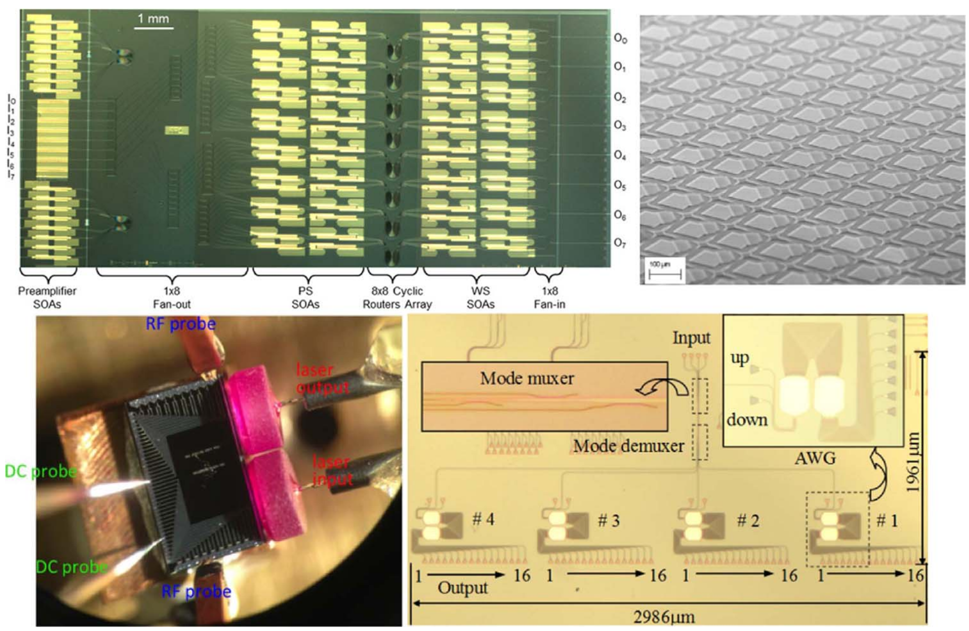

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Breakthroughs in Photonics 2014: Optical Interconnection Networks

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Abstract: This paper highlights the 2014 breakthroughs in the area of optical interconnection networks. As photonic components are being further integrated, particular attention is given to integrated optical interconnection networks for modern computer systems, beyond optical point-to-point interconnectivity. This field of research has become increasingly multidisciplinary with impressive system integration demonstrations.

Index Terms: Interconnection networks, optical switches, integration optical devices.

1. Introduction

Optical interconnection networks for computer systems have been an important research topic since the 1980s when the bandwidth capacity advantage of the optical domain became evident [1], [2]. Fueled by the development of high-performance computing, research in optical interconnection networks focused on enabling low-latency and high-throughput interconnectivity between shared electronic processing elements. In the last decade, the strong demand for data processing from the steady growth of the Internet combined with the advancement in optical device integration had an important impact on research related to optical interconnection networks which experienced an impressive level of development. In 2014, breakthroughs in optical interconnection networks have occurred in the two main types of optical networks, one of which uses an electrical switch and the other an optical switch. For the first type, the interconnection network makes use of low-loss high-bandwidth optical technology for enhanced data transmission through spectral efficient modulation formats (e.g., [3]), while maintaining the network switching in the electrical domain [4]. In this field, photonic integration has enabled footprint reduction of optical functions leading to more practical deployment of transceivers with better integration of the associated electronics.

The focus of this review is on the second type of optical networks where the switching functions are maintained in the optical domain without signal conversion between the optical switch and the optical interconnection. Motivated by the signal conversion latency overhead and power consumption required at the electrical switch interface, an all-optical switching is a candidate to allow further scaling of computer systems. The breakthroughs discussed focus on optical technology prototyping towards an optical switch matrix. Considering the increasingly strong multi-disciplinary field, the works reported are the outcome of many years of collective contributions of many others not necessarily reported in this review. Attention is given to the creative exploitation of optical switching domains, interconnection network in silicon-on-insulator technology, heterogeneous integration, and inclusion of the network controller in the prototyping. Overall, it has been an exciting year, hinting at high expectations for the coming years.

2. Rise of Mode and Polarization Interconnection Switching Domains

In 2014, optical integration enabled the investigation of more switching domains such as mode and polarization. Exploited in long-haul communication for increased transmission capacity, the advancement of encoding orthogonal information on different modes leads to a reduced number of laser sources for the same throughput. While there is certainly a tradeoff in terms of power consumption to maintain the necessary optical power, the reduction in components is a strong motivation. The Chinese research group led by Dr. D. Dai at Zhejiang University has pushed the exploitation of mode-division multiplexing with the demonstration of a 64-channel hybrid on-chip demultiplexer using 16 wavelengths, each exploiting four modes (see Fig. 1) [5]. The four modes ingressing the switch matrix are multiplexed using broadband adiabatic directional couplers, and then demultiplexed using four 16-channels arrayed-waveguide gratings (AWGs). The TM-based passive switch is fabricated in a Silicon-on-insulator (SOI) platform. On top of mode-division multiplexing techniques, the polarization orthogonality can be exploited leading to further capacity enhancement by a factor of two for each mode of an optical carrier. An on-chip link in SiP was demonstrated by US researchers at Columbia University, where two modes and two polarizations of a single optical carrier were transmitted for an aggregated bandwidth of 40 Gb/s [6]. This leads the way to potentially switch data and address interconnected nodes based on polarization and/or on modes.

3. The Pursuit of Space–Wavelength Interconnection Networks

The more conventional optical switching domains exploited in interconnection networks remains space, through a broadcast-and-select approach, and wavelength through wavelength division multiplexing techniques. The two domains continued to fuel creative implementation of architecture topologies. The European research group from Eindhoven Institute of Technology (TU/e) published, in 2014, a more complete study of the first integrated 8-port space–wavelength switch matrix in III–V fabrication technology [7]. As shown in Fig. 1, the 14.6 mm by 6.7 mm chip prototype integrated no less than 136 semiconductor optical amplifiers (SOAs) all wire-bonded to a printed circuit board achieving a final yield of 92% with 84% of the paths optically verified. The architecture exploits nanosecond-switching SOAs as pre-amplifiers and as selective gates, along with wavelength selective AWGs. The resulting signal path includes three SOAs only with a maximum total current of 180 mA. In 2014, the same group has demonstrated an 8 by 7 crossbar switch matrix implemented in SOI technology, exploiting fifth-order race track based active resonant switch elements enabling switching of a 40 Gb/s payload [8]. Thermal switching speed in the microsecond range is achieved with each switch consuming 120 mW. The non-uniform path loss increases linearly from 12 to 22 dB for one to eight rings in the optical path, respectively.

4. The Increased Opportunities of Silicon Photonics

Built on the argument that SiP technology offers a low-power solution to address the interconnectivity demand, US-based researchers at Alcatel-Lucent Bell Labs have demonstrated an on-chip optical bus for a 10×10 Gb/s optical interconnection network [9]. The 5 mm by 3 mm chip fabricated in SOI technology integrates a total of 72 devices with the signal conversion performed on the chip (see Fig. 1). The 10-port switch exploits a bank of silicon microring modulators aligned to each wavelength and multiplexed on a bus configuration. At the receiver, ten ring-based drop filters demultiplexed the wavelengths to germanium photodetectors. The optical switch matrix is dynamically reconfigurable by thermally tuning the ring resonators with tens of microsecond switching speed. In 2014, the SiP promising platform was further enhanced with microelectromechanical systems

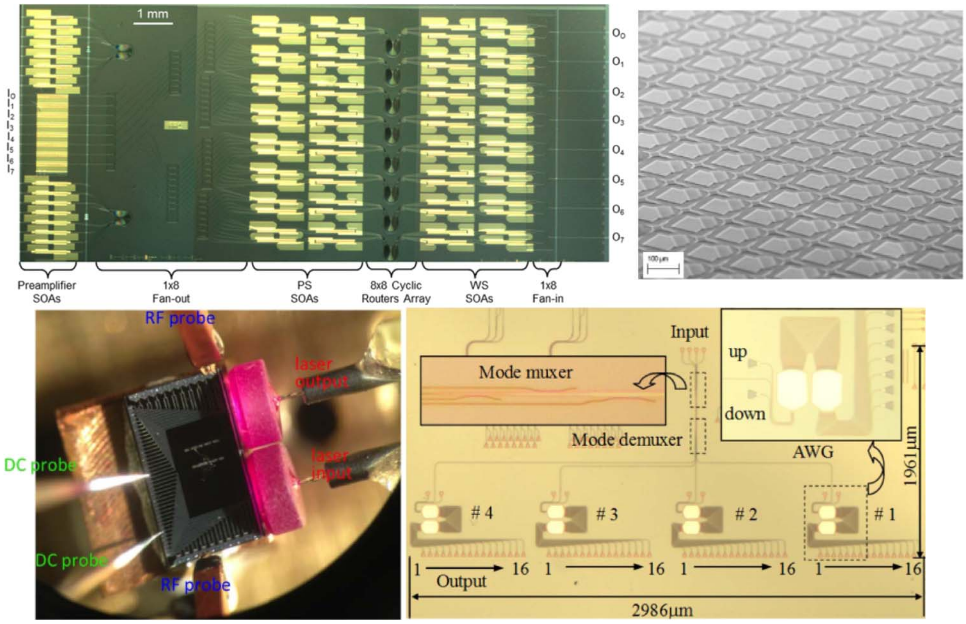

Fig. 1. (Top left) Eight-port space–wavelength switch matrix with 136 wire-bonded SOAs [7]. (Top right) 50-ports MEMS based SiP switch matrix [10]. (Bottom left) 10-port SiP interconnection network with on-chip 10 Gb/s signal conversions [9]. (Bottom right) 64-channel mode-wavelength SiP switch matrix [5].

(MEMS). The research group led by Dr. M. Wu from The University of California at Berkeley has demonstrated a 50 $\times$ 50 MEMS based matrix switch in a 9 mm by 9 mm chip (see Fig. 1) [10]. An orthogonal grid is indeed leveraged with movable directional couplers located at the waveguide crossing actuated with 16 V signal switching the light from the through waveguide to the drop waveguide. An impressive total of 2500 MEMS cantilever switches has been fabricated. This makes for the largest optical circuit switch matrix implemented in SiP. With scalability, integrated network will require optical amplification. The possibility of integrating SOAs onto Silicon is also moving forward with further improvement in heterogeneous integration of InP-based devices by various research groups [11], [12]. Optical gain will enable further scalability of integrated optical interconnection networks in terms of port count.

5. Towards Heterogeneous Packaging

As optical integration is reviving the research field of optical interconnection networks in 2014, packaging technology development is further pushing the possibilities by bringing electronic circuits closer to the optical functions. Through stacking by flip-chip bonding, compatibility between photonic integration and electrical integration is being enabled by exploiting the third dimension. The Japanese Photonics Electronic Technology Research Association (PETRA) has taken this direction and have contributed several works in 2014 addressing the light source integration, as well as the feasibility of making use of a SiP based interposer [13]. While the approach focuses on point-to-point interconnectivity, the demonstrated interposer includes on-chip optical active devices.

6. The Understated Optical Interconnection Network Controller

One of the important aspects of optical interconnection networks is its control, which remains electrical for all-optical switches. The controller is an essential aspect of optical interconnection networks and is often omitted in the assessment and feasibility of optical interconnection networks due to the challenging nature of multi-disciplinary research. In 2014, a 64-node system has been proposed by the researchers from IBM, exploiting SOAs for a 256 reconfigurable photonic-switch planes [14]. As for prototyping, there were several interesting demonstrations over the years, which included some form of a switch matrix controller: an important stepping stone towards the viability of optical interconnection. Indeed, scheduling and contention resolution induces latency which, if not properly addressed, will cancel the benefits of low-latency, high-throughput optical transmission. In 2014, a collaborative research effort between Cambridge University and TU/e has led to the demonstration of a dynamic routing through a round robin scheduling approach implemented in an FPGA with 4-ns transition time [15]. Routed packets of 940 ns with 60 ns guard time within 1 μs time-slot were demonstrated. Unfortunately, timing and synchronization remain unaddressed. The coming years should bring us more system-level integration of on-chip optical switch matrices for application in modern computer systems.

7. Conclusion

While the optical interconnection network research field has been active for decades, deployment remains at the prototyping level where switching is in the optical domain. The advancement of optical integration has opened a new window of opportunity towards better system integration of an electrically controlled optical switch matrix. The research field is flourishing with many more impressive works out there worthy of our attention. Keep your eyes open in 2015 for exciting breakthroughs in the field of optical interconnection networks.

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