Highly-Scalable, Low-Crosstalk Architecture for Ring-Based Optical Space Switch Fabrics

Qixiang Cheng*, Meisam Bahadori, Sébastien Rumley, and Keren Bergman

Department of Electrical Engineering, Columbia University, New York, NY 10027, USA

*Author email: qc2228@columbia.edu

Abstract—A ring-based switch architecture that combines the Clos network with populated switch-and-select stages is proposed, achieving significantly reduced crosstalk compared to other non-blocking architectures. Detailed physical-layer simulation results show a 128×128 switch exhibits a power penalty of 18dB, improving >10dB compared to the Benes switch.

I. INTRODUCTION

Silicon ring resonators have been extensively studied as modulators, filters, multiplexers, and switches owing to their advantages of small footprint, low power consumption, and most importantly, compatibility with well-established CMOS fabrication processes. So far, ring-based switch fabrics have mostly been exploited as cascading 1×2 or 2×2 switching elements in classic topologies, such as Cross-bar and Benes [1]. However, the accumulation of crosstalk (CT) and insertion loss (IL) limits the performance and thus ultimate size of such switch fabrics. Recently, a modular switch architecture was proposed by applying 1×N and N×1 ring-based spatial (de-)multiplexers as input and output interfaces, respectively [2]. This “switch-and-select” architecture limits the number of drop rings per path to 2; however, in return it requires a larger number of rings (2N²). While this modular scheme relaxes the challenge on design and fabrication, monolithic integration that reduces the overhead in terms of assembly, calibration, synchronization, and energy efficiency is preferable. In general, for large-scale monolithically-integrated switch fabrics, careful trade-offs need to be examined between the number of cascaded routing elements, the total number of required elements, and the aggregated crosstalk impairments.

In this work, we propose and analyze a ring-based Clos switch architecture populated with switch-and-select-bus stages. This design combines a limited number of switch stages with a substantially smaller number of rings and offers immunity to first-order crosstalk, thus leading to high performance and high scalability.

II. HYBRID MULTISTAGE ARCHITECTURE

A number of multistage network architectures have been studied and implemented for optical switch fabrics. However, signal degradation resulting from loss (accumulated across the stages) and crosstalk (accumulated over other input signals) exacerbates as radix scales up. Our proposed Clos-of-switch-and-select architecture offers a suitable balance that keeps the number of stages to the modest value of three while largely reduces the required number of switching elements. A generic schematic of a Clos network is presented in Fig. 1(a), comprising n×m, r×r and m×n stages. We set here n to be equal to m and to be a power of 2. Under this condition, to obtain N inputs and outputs, r=N/n. The total number of required ring elements reaches the minimum (8N+N²) when n=2, while the upper bound (6N³/2) occurs when n=n=r.

Single-stage switch-and-select switches are deployed as sub-switching-networks within the three stages of Clos network, to minimize the number of drop rings per path. Each switch-and-select element is built by connecting n spatial de-multiplexers (1×n) to n multiplexers (n×1), as shown in Fig. 1(b). Each (de-)multiplexer comprises n ring resonators coupled to a bus waveguide to add or drop lightweight signals. This configuration maintains the number of drop (i.e. resonating) rings in any path through a stage at two, while scaling n only adds bypassing rings through the bus. Moreover, this drop-and-add scheme only allows second-order crosstalk as illustrated in Fig. 1(b). An example of 16×16 Clos-of-switch-and-select switch is illustrated in Fig. 1(c), constructed by twelve 4×4 switch-and-select sub-networks.

III. TOPOLOGICAL EVALUATION

The proposed hybrid architecture is subsequently compared with topologies that are commonly applied in photonics. The selected figure of merits include the worst-case number of drop rings incurred to traverse the switch, a proxy for loss and crosstalk, and the total number of rings for a given switch fabric size, a proxy for footprint and control complexity. For networks that are built from 2×2 switching cross-points, a structure of two rings sitting with a waveguide crossover is used.

The comparison is illustrated in Fig. 2. The cross-bar topology stands out for small-size networks in which only one
The performance of the proposed Clos-of-switch-and-select switch is subsequently evaluated using our advanced simulation platform, PhoenixSim [3]. Rib waveguide with dimensions of 450 nm × 220 nm on a 100 nm silicon slab is utilized with operating wavelength at 1550 nm. The design space of a single add-drop ring resonator is first explored, where the ring is coupled to two waveguides and both electro-optic and thermal-optic phase shifters are facilitated. The heater acts as a slow phase tuner to lock the ring to the resonance wavelength, while the p-i-n junction acts as a fast modulator for switching. Critical coupling condition is set for drop-state to minimize the insertion loss and crosstalk leakage. By defining the bound of drop loss to less than 0.5 dB, extinction of resonance to better than 30 dB, and the 3 dB bandwidth to larger than 25 GHz, the design space can be narrowed down as presented by Fig. 3(a). The radius, output gap, and input gap is therefore chosen as 9 μm, 155 nm and 150.5 nm, respectively, giving rise to a drop loss of 0.35 dB. The operating point for off-resonance can then determined by minimizing the crosstalk ratio to -29.3 dB with 0.1 dB through loss, taking into account the free-carrier absorption associated with the plasma effect (shown in Fig 3(b)).

Physical layer analysis of the proposed switch architecture can therefore be simulated by assembling the ring resonators with passive shuffles for various switch fabric scales. The detailed breakdown for power penalties is outlined in Fig. 4(a), indicating that up to 128 × 128 port monolithically-integrated silicon switch is feasible. It can be seen that this design exhibits an excellent immunity to crosstalk impairments. For moderate switch sizes, the ring-induced loss accounts for a large proportion; however, shuffle loss increases sharply and becomes dominant for large-scale switch fabrics. It should be noted that adding an extra SiN layer can be leveraged to further decrease the propagation loss of passive shuffle networks. In order to highlight the benefits of the proposed architecture, a comparison with the conventional Benes topology is made. Figure 4(b) shows that the first-order crosstalk limits the ultimate size of Benes switch to 64 port with a 19 dB power penalty, which is ∼10 dB higher than the equivalent proposed switch.

V. CONCLUSIONS

This paper proposed a highly scalable architecture for monolithically-integrated ring-based silicon switch fabrics. The highly scalable nature of Clos topology is used to complement the low crosstalk of switch-and-select switching networks, yielding low-crosstalk, and large-scale switch fabrics. Detailed physical-layer simulations confirm the feasibility of building a 128 × 128 port switch, with an improvement of more than 10 dB compared to equivalent Benes switch fabrics.

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