System Performance Assessment of a Monolithically Integrated WDM Cross-Connect Switch for Optical Data Center Networks

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The system performance of a photonic integrated 4×4×4λ WDM cross-connect switch including SOA based wavelength selective switch is experimentally assessed. The results show nanoseconds wavelength, space, and time switching operation for 10 Gb/s, 20 Gb/s, and 40 Gb/s data packets and error-free dynamic switching has been achieved with less than 2dB power penalty. The capability of supporting multiple 40 Gb/s WDM channels indicates the potential of the cross-connect switch to further scale to higher capacity and port count in optical data center networks.

Introduction

Driven by the cloud computing paradigm and Internet applications, data centers experience a steady annual increase of traffic. Emerging data center applications and workloads are creating new communication patterns where up to 75% of the total data center traffic is within data centers [1] (server to server and rack to rack). This huge increase of intra data center traffic requires architectural and technological changes to the underlying interconnect in order to enable scalable growth both in communicating endpoints and traffic volume, while decreasing the costs and the energy consumption.
Optical switching could be an attractive technology featuring data rate and data format agnostic operation, and fast (nanoseconds) switching speed. Recently the advantages of using fast (nanoseconds) optical cross-connect switches to realize novel and efficient flat DCN providing low latency and high capacity have been investigated in several projects [2-4]. To validate the DCN architectures [5], WDM optical cross-connect switches based on off the shelf SOA technology and optical components (SOAs, AWGs, optical couplers, etc.) have been employed. However, practical implementation requires the integration of 100’s of those optical components, resulting in power and cost inefficient large and bulky systems. Recently, the photonic integrated WDM cross-connect switch has been fabricated and statically characterized [6].
In this work, we experimentally assess the system performance and the dynamic operation of the photonic integrated 4×4×4λ WDM cross-connect switch including SOA based wavelength selective switches for nanoseconds wavelength, space, and time switching operation. Experimental results show error-free dynamic switching of 10 Gb/s, 20 Gb/s, and 40 Gb/s data packets with limited (<2dB) penalty.

System operation

The DCN architecture employing the distributed WDM optical cross-connect switches [5] is shown in Fig. 1(a). The schematic of the optical wavelength, space, and time cross-connect switch is illustrated in Fig. 1(b). The non-blocking optical cross-connect has N inputs, and each input carries M different wavelengths generated by the TORs. The modular cross-connect processes the N WDM inputs in parallel by the respective optical modules, and forwards the individual wavelength channels to any output ports according to the switching control signals. More information about the controlling of

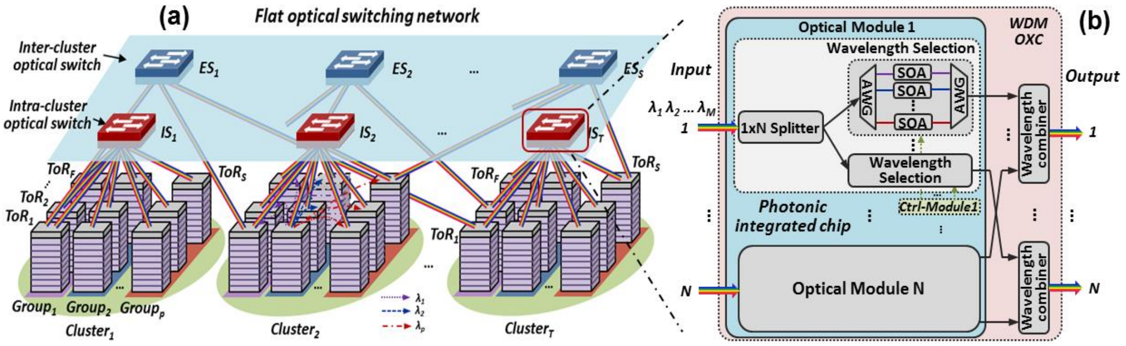

Fig. 1: (a) DCN architecture employing the distributed WDM OXC switches. (b) Schematic of the WDM optical cross-connect switch.

the switch is reported in [5]. Each optical module consists of a 1:N splitter to broadcast the WDM channels to the N wavelength selective switches (WSS). The outputs of the N WSSs are connected to the N wavelength combiners of the respective N output ports. Each WSS can select one or more wavelength channels and forward the channels to the output ports according to the control signals. The WSS consists of two AWGs and M SOA based optical gates. The first $1\times M$ AWG operates as wavelength de-multiplexer. Turning on or off the M SOA optical gates determines which wavelength channel is forwarded to the output or is blocked. The second $M\times 1$ AWG operates as wavelength multiplexer. Multicast operation is also possible with this architecture. The broadband operation of the SOA enables the selection of any wavelength in the C band. Moreover, the amplification provided by the SOA compensates the losses introduced by the two AWGs. It should be noted that the amount of SOAs is $N\times N\times M$, but typically only $N\times M$ will be turned on.

Figure 2(a) shows the photonic integration of 4 optical modules for wavelength, space, and time switching of 4 WDM inputs in parallel [6]. The chip has been realized in a multi-project wafer (MPW) in the Jeppix platform with limited space of the cell (6 mm × 4 mm) and does not include the wavelength combiner. Each of the four identical modules processes one of the four WDM inputs. At the input of the module, an 800 µm SOA is employed to compensate the 6 dB losses of the 1:4 splitter and partially the AWGs losses of the WSS. The passive 1:4 splitter is realized by cascading 1x2 multimode interferometer (MMI). The four outputs of the 1:4 splitter are connected to four identical WSSs, respectively. The WSS consists of two AWGs and four SOA based optical gates placed in between the two AWGs. The AWGs are designed with a free spectral range (FSR) of around 15 nm. The FSR has been tailored to fit the limited cell size offered in the MWP. The quantum well active InGaAsP/InP SOA gates have a length of 350 µm. The input and output facets of the chip are anti-reflection coated. The light shaded electrodes are wire bonded to the neighboring PCBs to enable the SOA gates. Lensed fibers have been employed to couple the light in and out of the chip.

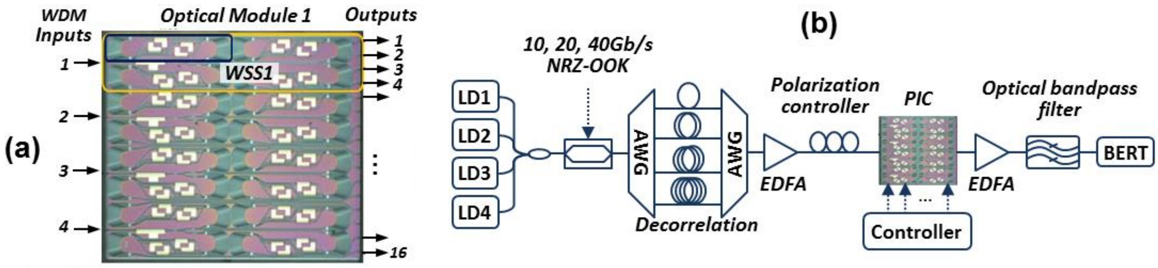

Fig. 2: (a) The fabricated WDM OXC chip. (b) Experimental set-up employed for performance evaluation.

Experimental results

To assess the performance of the 4×4 photonic cross-connect switch, the experiment set-up shown in Fig. 2(b) is employed. Four WDM optical channels with packetized NRZ-OOK (PRBS 2^{11}-1) payload at data rates of 10 Gb/s, 20 Gb/s and 40 Gb/s are generated at 1525.0 nm, 1528.9 nm, 1532.9 nm and 1536.8 nm. The packet has the duration of 540 ns and 60 ns guard time. The four WDM channels are de-correlated, amplified and injected to the photonic integrated WDM cross connect via a polarization controller. Module 1, as one of the four identical modules, has been selected for the switching performance assessment. The total power launched into the input port 1 is 2 dBm (-4 dBm per channel). The input SOA, acting as a booster amplifier, is continuously biased with 100 mA of current. The shorter SOAs in the WSS acting as optical gates on the different channels are controlled by an FPGA-based switch controller. The temperature of the PIC is maintained at 25 ℃.

The dynamic switching operation of the single WSS highlighted in Fig. 2(a) is first investigated. The WDM packets arrived at WSS 1 in Module 1 are de-multiplexed and controlled individually by the gate SOAs. The switch controller will turn on one or multiple gates to forward the packets, and the selected wavelength channels are multiplexed at the WSS output. The traces of the WDM input packets (shown in black) are illustrated in Fig. 3(a). Each packet is labelled with the wavelength channel needs to be switched to the output 1, while packets labelled with "M" means that multiple gates are enabled for multicasting operation. The switch controls (Ctrl 1-4) generated by the FPGA and applied to the 4 SOA gates of the WSS are also illustrated in Fig. 3(a). The signals are synchronized with the packets and "on" states correspond to a bias current of 40 mA. The packets of the four channels are fast switched (~ 10 nanoseconds) and the outputs (CH 1-4) are presented in Fig. 3(a). The traces indicate that the packets are properly switched according to the control signals with a contrast ration larger than 28 dB.

As a second system assessment, the dynamic switching operation of the four WSSs has been investigated. In this case, packets at wavelength 1 (1525 nm) is switched to one of the 4 output ports by controlling the CH 1 SOA gates of the 4 WSS. The traces of the input packets, the control signals, and the switched outputs are reported in Fig. 3(b). The input packets are labelled with the destination output ports and broadcasting ("B") to two and more ports are also enabled by turning on multiple SOA gates. It can be seen from the Fig. 3(b) that the fast dynamic switching operation in space, wavelength as well as time domains are fully supported by the WDM cross-connect switch.

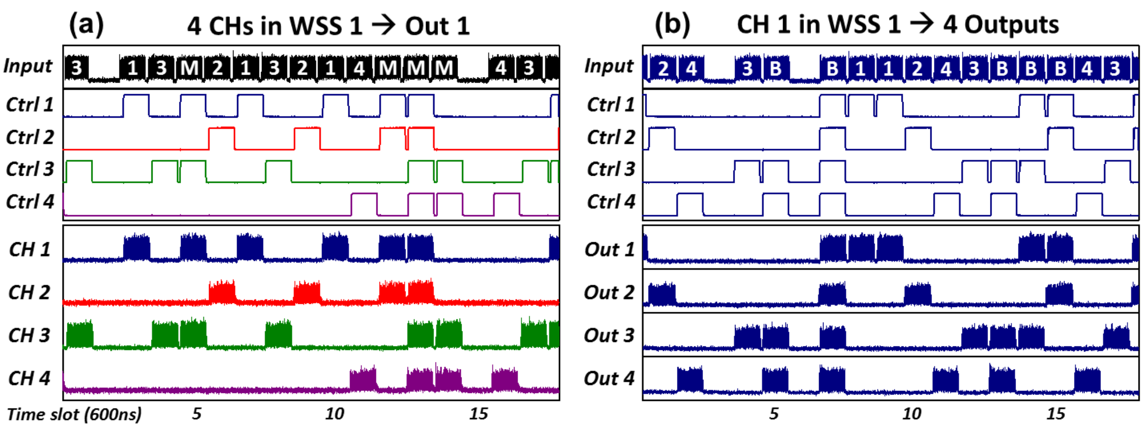

Fig. 3: (a) Traces for WSS1. (b) Traces for 4 outputs.

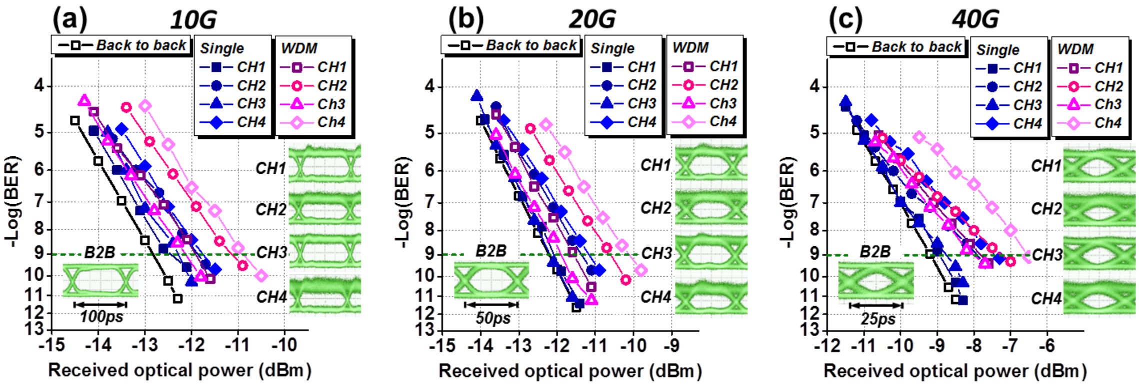

Fig. 4: BER curves for single channel and WDM channel input at (a) 10Gb/s; (b) 20Gb/s; (c) 40Gb/s.

To quantify the performance of the switch, the BER curves for each WDM channel at different data rates are measured and the results are shown in Figs. 4(a)-(c). The back-to-back (B2B) curves are also included for reference. The gate SOA for the channel under test is supplied with 60 mA driving current and the output is amplified and sent to the BER tester (BERT). When the single wavelength channel is input to the PIC (shown in blue curves), error-free operations with less than 0.5 dB have been measured for CH 1 and CH 3 at different data rates. While for the CH2 and CH 4, the penalty is around 1 dB at 10 Gb/s, 20 Gb/s, and 2 dB at 40 Gb/s data rate. The eye diagrams of the switched output are also reported and confirm the signal degradation mainly due to accumulated noise for CH 2 and CH 4. When all the four WDM input channels are fed into the switch, the BER results (shown in red curves) indicate slight performance degradation with an extra penalty of around 0.5 dB for CH 1 and CH 3 and 1 dB for CH 2 and CH 4 compared with single wavelength operation for the different data rates.

Conclusions

We have assessed the system performance of the photonic integrated 4×4 WDM cross-connect switch for optical DCN. The experimental results confirmed the capability of the cross-connect chip to dynamically switch within few nanoseconds WDM data packets in space and wavelength with low contrast ratio (< -28 dB). Error-free operation with < 2 dB penalty has been measured for 40 Gb/s WDM channels, which indicates the potential scale of the cross-connect switch to higher data rate and port count.

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