Space Switching Enabled Tunable Wavelength Converter and Its Application in Large Scale Optical Interconnect Architecture

Zhaowen Xu*, Luying Zhou and Xiaofei Cheng

Institute for Infocomm Research (I2R), A*STAR, 1 Fusionopolis Way, #21-01 Connexis (South Tower), Singapore 138632

*zxu@i2r.a-star.edu.sg

Abstract: We propose a large scale Clos structure based optical interconnect by employing cyclic arrayed waveguide grating routers (AWGRs) and novel space switching enabled tunable wavelength converters (SS-TWCs). The 1:2 or 1:4 SS-TWCs expand the scale of the optical interconnect up to 8 times of standard Clos structure while using the same AWGR modules. Experimental results are given to demonstrate the feasibility of the proposed optical interconnect.

Keywords: Optical Interconnect, AWG, Tunable Transmitter, Wavelength Converter

1. Introduction

Wavelength converter is one of the key components for wavelength-division-multiplexing optical networks and photonic switch blocks [1]. Arrayed Waveguide Gratings (also called arrayed waveguide grating router, AWGR) combined with arrays of tunable wavelength converters provide a flexible and scalable basis for constructing large switch fabrics. Transparent wavelength converters [2-3] facilitate both optical circuit and packet switched networks not only because high bit-rates are supported, but also because they are transparent to modulation format, e.g. OOK, QAM, QPSK, OFDM, and may relax the requirements of O-E-O conversion [4].

Today, the scale of data centers is expanding steadily from tens of thousands servers to hundreds of thousands of servers in a single facility due to the rapid growth of Internet applications, storage and computation requirements. It faces the challenges of developing a large scale data center network which meets the requirements of high bandwidth capacity, simple cabling and low power consumption [5-7]. Wavelength converter based solutions have been proposed to build high performance and large scale optical data center switch architecture, including the datacenter optical switch (DOS) architecture [8], IRIS solution [9], and PetaX optical switch [10]. All these solutions employ N*N AWGR with cyclic wavelength routing characteristic and tunable optical wavelength converter (TWC) [8-11]. The N*N AWG allows any input port to reach any of the output ports by tuning input wavelength, and the switching speed of the AWG-based cross connects is determined by the tuning speed of the wavelength converters. For both DOS architecture and IRIS solution, the supported port number equals to N, the port number of AWGR. PetaX switch fabric is a Clos network, in which N*N AWGRs are used as core switch modules in each stage [10]. Due to the cyclic routing characteristic, multiple input ports may be routed to the same output port simultaneously with different optical wavelengths. By using Clos structure, the maximum port number can be significantly increased to N^2, where N is the port number of AWGR. Although it has been reported that the port number of AWGR can reach 128 [11] and even 400 [12], the commercial available product is normally 32*32 and below.

In this paper, we present a space switching enabled tunable wavelength converter (SS-TWC) structure and propose a novel optical interconnect architecture based on enhanced three-stage Clos structure. The enhanced Clos structure consists of AWGRs and SS-TWCs. Considering that current quantum-dot semiconductor optical amplifier (SOA) based tunable
wavelength converter can easily support several free spectral ranges (FSR) [13], tunable wavelength converters with space switching function of 1:2 and 1:4 are proposed by employing coarse WDM demultiplexers (also called CWDM couplers) to separate wavelengths in different FSRs. The cyclic wavelength routing characteristic allows AWGR to work in multiple FSRs. Combining the cyclic AWGR and SS-TWC, the scale of optical interconnect can be increased to 8 times of conventional Clos structure.

2. Proposed optical interconnect

2.1 1:2 SS-TWC based Clos optical interconnect

The elements of proposed large scale optical non-blocking interconnect are shown in Fig.1. The SS-TWC consists of a tunable laser, an SOA, and a coarse WDM demultiplexer. Here, the wavelength tuning range of the SOA based wavelength converter covers two and half FSRs of AWGR, which is quite normal for current SOA. Using a 32*32 AWGR with a channel spacing of 50GHz as an example, one FSR is 12.8nm. The required wavelength range of such wavelength converter is 32nm, which is much smaller than the reported result [13] where the SOA based WC is tuned in 150-nm wavelength range. A coarse WDM demultiplexer is used to separate the converted wavelengths into two bands, i.e., short band \( \lambda_s \) and long band \( \lambda_L \), with a guard band of \( \text{FSR}/2 \), as shown in the inset of Fig.1a). For any input wavelength, the converted wavelength can be flexibly switched to output port 1 or output port 2 by tuning its wavelength to \( \lambda \) or \( \lambda + n \cdot \text{FSR} \). Here \( n \) is an integer. In default case, \( n \) equals to 1. Only in case that wavelength \( \lambda + n \cdot \text{FSR} \) falls in the guard band, \( n \) equals to 2. Considering the cyclic wavelength routing characteristic of AWGR, wavelengths \( \lambda \) and \( \lambda + n \cdot \text{FSR} \) share the same routing path in AWGR [14]. As a result, SS-TWC performs a 1:2 space switching function and does not affect the wavelength routing in next stage of Clos structure.

The input module (IM), central module (CM) and output module (OM) of the Clos structure are shown in Fig.1 b), c), and d), respectively. Different with previous Clos network [7], the wavelength conversion of the proposed Clos switch is performed in IM and CM. Each output port of AWGR of IM and CM is directly connected to an SS-TWC, and each input port of AWGR of CM and OM is split into two with a simple optical splitter or a coarse WDM demultiplexer.

Fig. 1 Elements of proposed large scale optical interconnect, including a) SS-TWC with space switching function of 1:2, b) input module, c) central module and d) output module of the three-stage Clos structure.

An optical non-blocking interconnect can be constructed by using these three modules, as shown in Fig.2. Here \( N \times N \) AWGRs are used. Each CM connects to only one output of each IM and one input port of each OM with any of the two wavelength bands, \( \lambda_s \) and \( \lambda_L \). By connecting all these modules, a \( (2N^2) \times (2N^2) \) optical interconnect fabric is formed. Because
the port number of a CM is increased to twice of AWGR port number by SS-TWC and optical splitter, the numbers of connected IM and OM are accordingly increased, i.e., the number of modules of IM, CM and OM in each stage is increased from N to 2N. As a result, the proposed fabric doubles the input port number compared with conventional Clos switch.

In this fabric, input port $i$ can be connected to output port $j$ through any CM. The number of alternative paths between input $i$ and output $j$ is 2N. Considering only one output of SS-TWC is available simultaneously, the valid path number is N, which equals to the input number of IM. Thus it is a rearrangeably non-blocking optical interconnect.

A control plane is required in this architecture similar with other TWC and AWGR based optical switches. Here, an optical interconnect scheduling scheme is applied to establish the connection from input port to output port in two stages. In the first stage, the output port will be examined whether it is available for the input port, and algorithm such as iSLIP can be applied to determine the matching of input port and output port [15]. If the input and output ports are matched, in the second stage, a path will be found, e.g., using an approach similar to the one proposed in paper [16], where a set of binary vectors are used to represent the path availability of IMs to OMs through the central modules CMs. The available path from an IM to an OM can be determined via checking the availability status of their respective vectors. As in a general Clos switch structure, the paths connecting a specific IM-OM pair through the central module CMs are independent from the paths linking other different IM-OM pairs. The scheme can be performed in distributed manner for the input and output modules, but the output modules will be arranged in groups as the outputs of a CM module are related to multiple OMs due to the SS-TWC features. Detailed scheduling algorithm will be reported separately later.

2.2 1:4 SS-TWC based Clos optical interconnect

From Fig.2, it can be seen that the input wavelength of SS-TWC may locate in either $\lambda_s$ or $\lambda_L$. Another coarse WDM demultiplexer is proposed to separate these two wavelength bands
before wavelength conversion, as shown in Fig. 3 a). With such structure, two SOA-based wavelength converters are combined together as one 1:4 SS-TWC. The 1:4 SS-TWC switches the input wavelength to four outputs according to its input and output wavelength bands. The three stages of the optical interconnect are also shown in Fig. 3. Each input port of AWGR in CM and OM is split into four by optical splitter and coarse WDM demultiplexer. The WDM demultiplexer can be replaced by a power splitter to reduce its cost if the power budget is more than enough.

Fig. 3 a) Proposed 1:4 SS-TWC, and b) IM, c) CM and d) OM of the three-stage interconnect structure.

Fig. 4 (4N²) × (4N²) optical strictly non-blocking interconnect fabric using N×N AWGRs and 1:4 SS-TWC.

Using the 1:4 SS-TWC, a (4N²) × (4N²) optical strictly non-blocking interconnect fabric is constructed as in Fig. 4. The number of modules of IM, CM and OM in each stage is increased to 4N. The alternative path number for the connection from input port \( i \) to output
port \( j \) is \( 4N \) since each CM is a \( 4N \times 4N \) switch. Considering each 1:4 SS-TWC has only two active output ports simultaneously, the valid path number is \( 2N \), which is twice of the input number of IM. Following Clos theorem, this fabric is strictly non-blocking, and a new connection can always be added without rearrangement. Here, the control plane is not specified since the connection of control plane is as same as what shown in Fig.2.

2.3 Splitting input and output ports for higher port number

To further increase the connection port number, we split the input port of IM into two by a power splitter and split the output port of OM into two by a coarse WDM demultiplexer, as shown in Fig.5. In this structure, the half of the transmitters can receive short band wavelength, \( \lambda_s \), and the others can receive long band wavelength, \( \lambda_L \). The transmitters can be tuned to any wavelength in both wavelength bands, but the pair of transmitters connect to the same input of IM can never be tuned to same wavelength band simultaneously. In such case, the two inputs share the \( 2N \) alternative connection paths.

Due to the cyclic wavelength routing characteristic of the AWG, the tunable lasers connected to the same input port of an IM AWGR can be routed to different output port by selecting different wavelengths, as illustrated in Fig.5. One constraint is that the short band receivers can only be connected to the CMs with short band wavelengths output but can never connect to the CMs with long band wavelengths output. Fortunately, the available alternative path number for both band receivers is \( N \), which equals to the number of receivers in each band. Since alternative path number equals to the input number of IM, the enhanced interconnect scheme is rearrangeably non-blocking. By using the wavelength division multiplexing technique, the supported connection port number is further doubled, which is \( 8N^2 \). Considering the size of commercial available AWGR is \( 32 \times 32 \), the proposed optical fabric can support 8192-port optical interconnect simultaneously. The port number may be further increased when AWGR with larger port number [11-12] is available.

3. Experiment and results
An experiment is setup to validate the feasibility of the proposed scheme, shown in Fig.6. Three 32×32 AWGRs with channel spacing of 50GHz, FSR of 12.8nm and two SOA-based SS-TWCs are used to simulate the two alternative paths highlight in Fig.5. The polarization dependent gain of the SOA is about 0.3dB. For path 1 (solid-line link in Fig.6), the wavelength of TL1 is tuned to 1552nm, and routed to port A1 by AWGR-I2. The wavelength is converted to 1547.6nm in SS-TWC1 and routed to port B2 through the coarse WDM demultiplexer, and converted to 1573.2nm in SSTWC2 and finally routed to the receiver by AWGR-O1. Here, both SS-TWC1 and SS-TWC2 consist of two 1:2 SS-TWCs. However the input single wavelength optical signal only passes through one 1:2 SS-TWC in each TWC. The other one is inactive. In another word, the input optical signal passes through two 1:2 SS-TWCs in each alternative path. Also because of the shortage of enough optical components to setup two 1:4 SS-TWCs, we simplify the experiment setup by removing the inactive wavelength converters. As shown in Fig.6, two independent 1:2 SS-TWC are used to simulate the three stage Clos switching structure. The 1-dB bandwidth of CWDM demultiplexer is 15nm with 20nm channel spacing, which covers more than one FSR of AWGR. A guard band of 5nm is reserved to avoid significant crosstalk between two wavelength bands. For path 2 (dot-line link), the wavelengths are 1551.6nm, 1573.2nm and 1548nm before and after wavelength conversions, respectively. The measured insertion loss of AWGR, circulator, and WDM demultiplexer are 3.1dB, 0.8dB and 1.1dB, respectively. In each SOA, the input signal power is tuned to -1.5dBm by the optical attenuator (ATT) and the CW seeding power is set to -6dBm. The optical power of converted wavelength is about 5.4dBm.

The experimental results are shown in Fig.7. Here, 10-Gb/s PRBS is used to simulate data traffic. Eye signal to noise ratio is investigated first to demonstrate the wavelength conversion function of the SS-TWC. An Agilent DCA 86110B oscilloscope is used for eye SNR measurement. Results show the conversion range of this SS-TWC is much larger than
required 2.5 FSR. The BER performance at output of each module (i.e. IM, CM and OM) is also measured. BER penalties of 2.1dB and 2.3dB are observed after passing through the optical interconnect by path 1 and 2, respectively.

4. Conclusion

In this paper, we proposed a large scale three-stages Clos optical interconnect which is composed of space switching enabled tunable wavelength converters (SS-TWC) and AWGRs. The SS-TWC is able to convert and switch wavelengths. By using the SS-TWC, the port number of the optical interconnect is increased up to 8 times of conventional Clos interconnect, while using the same size 32x32 AWGRs and having non-blocking feature. The port number can be further increased by employing larger size AWGR.

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References and links