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Space switching enabled tunable wavelength converter and its application in large scale optical interconnect architecture

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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.

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

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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 50 GHz as an example, one FSR is 12.8 nm. The required wavelength range of such wavelength converter is 32 nm, 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 λ_s and long band λ_L, with a guard band of $FSR/2$, 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 λ or $\lambda + n \cdot FSR$. Here n is an integer. In default case, n equals to 1. Only in case that wavelength $\lambda + FSR$ falls in the guard band, n equals to 2. Considering the cyclic wavelength routing characteristic of AWGR, wavelengths λ and $\lambda + n \cdot FSR$ 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 the 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.

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, λ_s and λ_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 λ_s or λ_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.

Using the 1:4 SS-TWC, a $(4N^2) \times (4N^2)$ optical strictly non-

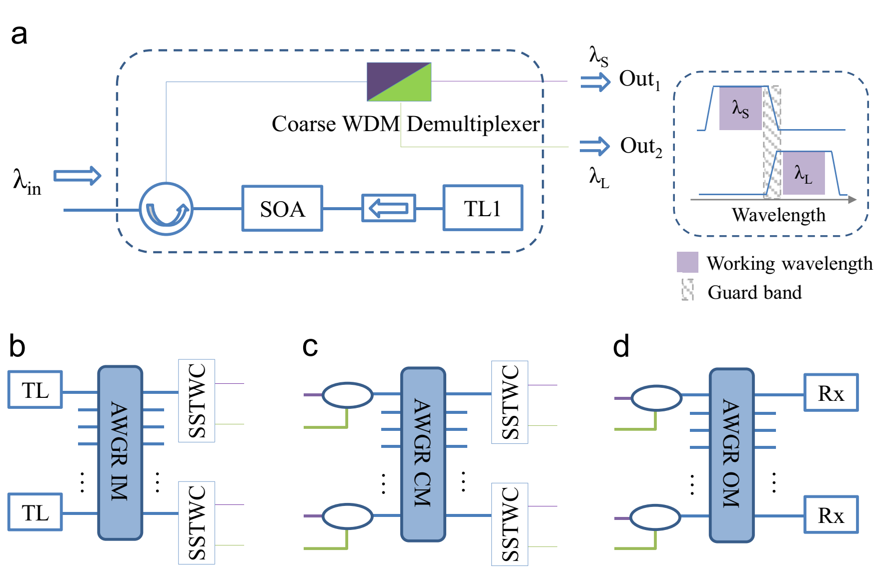

Fig. 1. Elements of proposed large scale optical interconnect, including (a) SS-TWC with space switching function of 1:2, (b) input module, (c) central module and (d) output module of the three-stage Clos structure.