Design of An All-Optical WDM Lightpath Concentrator

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Abstract—A design of a nonblocking, all-optical lightpath concentrator using WOC and WDM crossbar switches is presented. The proposed concentrator is highly scalable, cost-efficient, and can switch signals in both space and wavelength domains without requiring a separate wavelength conversion stage.

I. Introduction

A *concentrator* is a switch in which the number of input fibers is strictly greater than the number of output fibers. Thus, a concentrator drops some input signals and switches each of remaining signals to an output fiber on possibly a different wavelength. If the switching is done in the electronic domain, it is called an electronic concentrator or simply a concentrator. If the switching is performed in all-optical domain, then it is called an *all-optical lightpath concentrator* or simply *lightpath concentrator*.

With the advancement of WDM technology there has been an exponential growth in the size of interconnect, its complexity, the number of O/E/O converters, and its cost. There is a large mismatch between the capacity and speed of the optical transmission compared with the electronic counterpart which results in a bottleneck of the electronic switches and concentrators in WDM networks. This mismatch motivates design of all-optical switches and lightpath concentrator which can keep data in optical domain eliminating the need for costly and inefficient O/E/O conversions.

There are several practical deployments of optical networks, where it is necessary to switch signals from N fibers to M fibers, where $N > M$ [1]. For example, the function of a hub in metro networks is to collect N lightpaths from several regional hubs and transfer them to M lightpaths in the backbone network. Thus, a hub is a lightpath concentrator [1]. Lightpath concentrators have also been used in the design of all-optical switch architectures [2], [3], [4].

With the advancement of WDM technologies, there has been a need for cost effective WDM interconnects. The WDM crossconnects has separate stages for space and wavelength switching in the traditional switching paradigm. These designs are expensive and the switching costs increases significantly with the increase in the number of lightpaths carried by the fiber. A new paradigm for WDM interconnects' design is evolving in which space and wavelength switching is performed *simultaneously* and *seamlessly* [2], [3]. This design for WDM crossconnects eliminates the need for separate wavelength conversion stages.

In this paper, we present a design of an all-optical lightpath concentrator based on the wavelength exchange optical crossbar (WOC) and the WDM Crossbar Switches [2], [3]. The design of an all-optical lightpath concentrator presented in this paper makes use of WOC properties and can similarly achieve a balance between wavelength switching and conversion costs and does not require a separate wavelength conversion stage.

II. Related Work

A design of a WDM Optical Interconnect based on the concept of concentrators was proposed in [4]. This switch achieves full connectivity by using low cost limited wavelength converters. However, the design is based on the traditional concept of performing space and wavelength switching in separate stages [5]. A new class of WDM crossconnects using WOCs that minimizes the switching and wavelength conversion costs was proposed in [2].

Three designs of all-optical lightpath concentrators were presented in [1]. The first design is a generalization of the optical crossconnects which requires $M \times M$ optical switches and has the smallest blocking probability. The second design based on the concept of partial concentrators, is less costly but has larger blocking probability. In the third design, the small lightpath concentrators are used as the building blocks to construct a large concentration network. Since the building blocks are blocking, the third design is also blocking. Moreover these designs perform only space switching and do not consider wavelength switching at all.

A. Preliminaries

A lightpath concentrator with F_1 incoming fibers and F_2 outgoing fibers, where each fiber carries W wavelengths is called an $N \times M$ lightpath concentrator, where $N = F_1 W$, $M = F_2 W$, and $N > M$. For the sake of simplicity we assume F_1, F_2, and W are all powers of 2. The set of incoming fibers is given as $F_1 = \{f_{11}, f_{12} \ldots f_{1F_1}\}$, the set of outgoing fibers as $F_2 = \{f_{21}, f_{22} \ldots f_{2F_2}\}$, and the set of wavelengths as $W = \{\lambda_1, \lambda_2 \ldots \lambda_W\}$.

If an $N \times M$ lightpath concentrator can achieve any permutations of at most M out of N input lightpaths, it is called *nonblocking*, otherwise it is called *blocking*.

A wavelength request model $(\lambda_i, f_{1x}, \lambda_j, f_{2y})$, $\lambda_i, \lambda_j \in W$, $f_{1x} \in F_1$, and $f_{2y} \in F_2$, means an incoming lightpath on fiber

f_{1x} at wavelength λ_i is to be routed to an output fiber f_{2y} at wavelength λ_j [2].

A new class of WDM crossconnects denoted by $W^\lambda(F \times F)$ was proposed in [2]. This crossconnect has F input and F output fibers, each carrying W wavelengths ($N = FW$). The design of this class is based on the basic 2×2 switch called WOC [2]. A WOC acts like bar state of a traditional crossbar when the control signal is off (see Figure 1(a)). Otherwise, it performs both space switching and wavelength conversion simultaneously (see Figure 1(b)). The design of a $2^\lambda(2 \times 2)$ (i.e. $W = 2, F = 2, N = 2 \times 2 = 4$) WDM crossbar switch is shown in Figure 2. The rectangles are switching elements and circles denote WOCs.
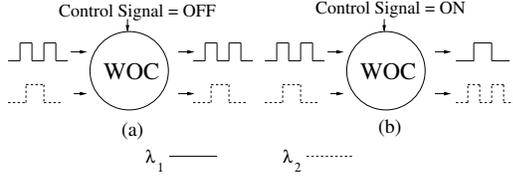

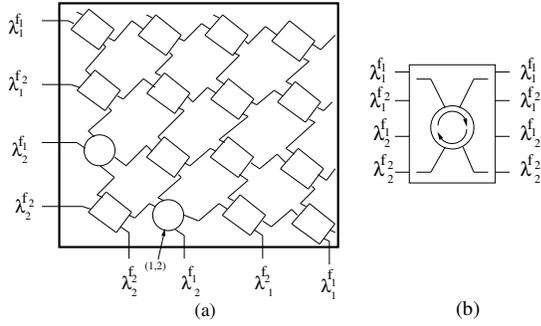Fig. 1. (a) WOC in bar state (b) WOC in cross state

Fig. 2. (a) $2^\lambda(2 \times 2)$ WDM crossbar switch (b) Its symbolic notation

The concept of WOC is based on the simultaneous exchange of power between two signals which has been experimentally demonstrated using *four wave mixing (FWM)*, *photonic crystals* and *nano-photonic devices* [2], [6]. The conversion and switching speeds of WOC are determined by the modulation speed of its pump [2]. Crosstalk may be a problem in WOCs because of the power exchanging process, but with the improvement and advances in the photonic and nano technologies, efficient design of WOC is possible in the near future.

III. Proposed Design

In this section, we discuss the design of the proposed all-optical lightpath concentrator and its scalability issues.

A. Basic Lightpath Concentrator

The *basic lightpath concentrators* is a device which can switch lightpaths from two input fibers to one output fiber. It can be used as the building blocks for design of an $N \times M$

lightpath concentrator. The design of a basic 4×2 lightpath concentrator, where each fiber carries two wavelengths is shown in Figure 3. The basic 4×2 lightpath concentrator can be used as a building block for recursively designing a basic lightpath concentrator, each fiber carrying n wavelengths. An $n-$wavelength ($n > 2$) can be designed recursively by using two $\frac{n}{2}^\lambda(2 \times 2)$ WDM crossbar switches and two basic $n \times \frac{n}{2}$ lightpath concentrators, where each fiber carries $\frac{n}{2}$ wavelengths. The design of a basic 8×4 lightpath concentrator, where each fiber carries four wavelengths is shown in Fig. 4.
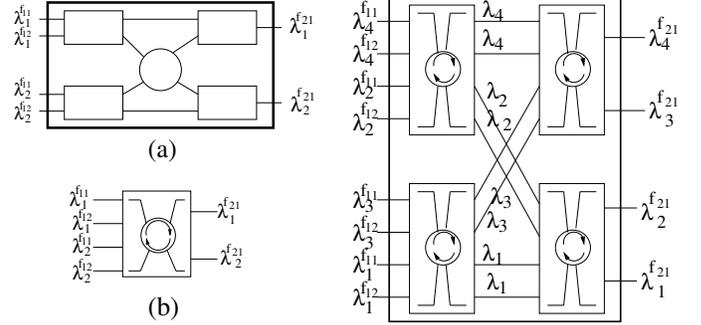

Fig. 3. (a) The basic 4×2 lightpath concentrator, each fiber carries two wavelengths (b) Its symbolic notation

Fig. 4. The basic 8×4 lightpath concentrator, each fiber carries four wavelengths

B. Scalability and $N \times M$ Lightpath Concentrator

The scalability of *basic lightpath concentrators* for designing an $N \times M$ lightpath concentrator can be broadly classified in the following two types:

1) *When $N = 2M$:* In this design of lightpath concentrators, there are two stages of WDM crossconnects. The first stage is the new WDM crossbar switch and the second stage is the basic lightpath concentrator. The first stage of switching interconnects makes sure that the signal is properly switched in space, and if possible also wavelength converted to the desired wavelength. The second stage of basic lightpath concentrators guarantees the input lightpath is properly wavelength switched and routed to the desired output port. This design requires two $\frac{W}{2}^\lambda(\frac{N}{W} \times \frac{N}{W})$ WDM crossbar switches, and two basic $M \times \frac{M}{2}$ lightpath concentrator, where each fiber carries $\frac{W}{2}$ wavelengths ($W > 2$). When, $W = 2$, it requires two $2^\lambda(\frac{N}{W} \times \frac{N}{W})$ WDM crossbar switches, and two basic $M \times \frac{M}{2}$ lightpath concentrator, where each fiber carries two wavelengths.

   A design of a 16×8 lightpath concentrator, each fiber carrying four wavelengths is shown in Figure 5.

2) *When $N \neq 2M$:* The design is again recursive in nature, and uses the smaller lightpath concentrators as the building blocks to achieve higher order of concentration. The main idea is to have two different stages of lightpath concentrators to guarantee space switching in the first stage and wavelength switching in the second stage. If possible, the wavelength switching can also take place in
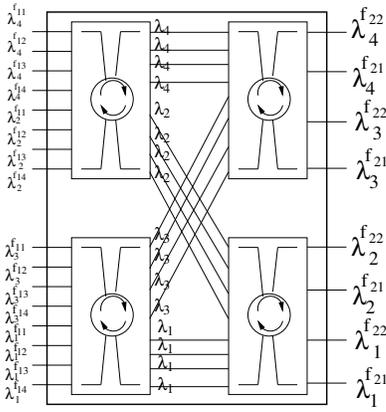
Fig. 5. 16×8 lightpath concentrator, each fiber carries four wavelengths

the first stage. This design requires two $\frac{N}{2}\times M$ lightpath concentrators, where each fiber carries $\frac{W}{2}$ wavelengths, and two basic $M\times\frac{M}{2}$ lightpath concentrators, where each fiber carries $\frac{W}{2}$ wavelengths ($W>2$). When, $W=2$, it requires two $\frac{N}{2}\times M$ lightpath concentrators, where each fiber carries two wavelengths, and two basic $M\times\frac{M}{2}$ lightpath concentrators, where each fiber carries two wavelengths.

A design of a 16×4 lightpath concentrator, each fiber carrying four wavelengths is shown in Figure 6.
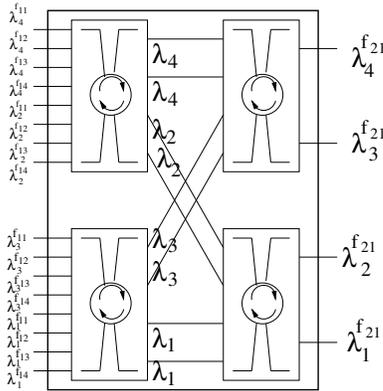

Fig. 6. 16×4 lightpath concentrator, each fiber carries four wavelengths

IV. PROPERTIES OF THE PROPOSED DESIGN

In this section, we establish two important properties of our all-optical lightpath concentrator design. The proofs are omitted due to lack of space.

Proposition 1: *The proposed design of a basic lightpath concentrator, in which each fiber carries n wavelengths is nonblocking in both space and wavelength domains.*

Proposition 2: *The proposed design of an all-optical $N\times M$ lightpath concentrator is nonblocking in both space and wavelength domains.*

From the recursive nature of the construction of the lightpath concentrator it follows that if a signal has to be dropped, it would be dropped by the lightpath concentrator at the last possible stage. An algorithm can be easily implemented

to drop signals by the lightpath concentrator based on a given criteria. We briefly present a routing algorithm for the proposed design in Figure 7.

Routing Algorithm for a request $(\lambda_i, f_{1x}, \lambda_j, f_{2y})$

1) Switch the signal from x^{th} input fiber to the basic lightpath concentrator connecting y^{th} output fiber at λ_j.
2) Convert the wavelength of the signal from λ_i to λ_j using the WOCs in the lightpath concentrator at any stage which is feasible based on other requests and on the availability of λ_j in that stage.
3) If the signal has to be dropped, drop it using the lightpath concentrator at the last possible stage.

Fig. 7. Routing algorithm for an all-optical $N\times M$ lightpath concentrator

V. CONCLUSION AND FUTURE WORK

With the advancement of WDM technologies, there has been an emerging need for efficient and cost effective design of an all-optical lightpath concentrator. The increasing mismatch between the speed of optical and electronic transmission and the expensive O/E/O conversion cost has motivated our interest in the design of an all-optical lightpath concentrator, where the lightpath always remains in the optical domain. WDM interconnects based on traditional switching requires separate space and wavelength switching stages, which increases the hardware cost of the interconnects and adversely effects their efficiency and scalability. In this paper, we present a design of an all-optical lightpath concentrator based on WOC and WDM crossbar switches [2] [3]. The proposed design is nonblocking in both domains, highly scalable, cost-efficient, and can switch signals in both space and wavelength domains without the need of separate wavelength conversion stage.

In future, we want to simulate the proposed design of the all-optical lightpath concentrator to study its performance in real-life scenarios. We also plan to perform a detailed cost analysis of the proposed lightpath concentrator design. An investigation of needs for priority based lightpath concentrators and its design is also an interesting future research direction.

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