Self-Routing Design of Nonblocking WDM Switches Based on Arrayed Waveguide Grating

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Abstract

Arrayed waveguide grating (AWG) is a promising technology for constructing high-speed large-capacity WDM switches, because it can switch fast, is scalable to large size and consumes little power. To take the full advantages of high-speed AWG, the routing control of a massive AWG-based switch should be as simple as possible. In this paper, we focus on the self-routing design of AWG-based switches with \(O(1)\) constant routing complexity and propose a novel construction of self-routing AWG switches that can guarantee the attractive nonblocking property for both the wavelength-to-wavelength and wavelength-to-fiber request models. It is expected that the proposed construction will be useful for the design and all-optical implementation of future ultra high-speed optical packet/burst switches.

1 Introduction

With the deployment of Internet and in particular the wavelength division multiplexing (WDM) technology, many new network applications have emerged, such as the Grid computation, High Definition TeleVision, Cooperative Tele-Surgery, etc., and it is foreseeable that more such bandwidth-intensive applications will need to be supported in future networks. For the efficient support of these bandwidth-intensive applications, network switch, which serves as the switching core of network routers and cross-connects to implement the actual switching function, is expected to have the switch capability in the order of several Tbit/s or even Pbit/s.

Although the electronic switch/router technologies are mature and easy to implement, their capacity growth is historically slower than the growth of optical link capacity [1]. Also, the power consumption of network switch/router has exponentially increased beyond the standard acceptable level in past years [2]. This is why switches/routers have increasing become a bottleneck for Internet communications. Furthermore, the upgrade of current electronic switch/router solutions is becoming extremely costly and difficult due not only to the high costs of the optical-electronic-optical (O/E/O) conversions, but more importantly also to the strong dependence of switching hardware upon data bit-rate and transmission protocols. Therefore, some future alternative solutions for switch/router design are mandatory. A natural choice (also seems to be the only one) is to use all-optical switch/router. This is why there is a renewed interest in optical switch/router architectures, as evident from several ongoing national-scale projects in the US, Europe, and Asia, see, for example, [3, 4]. Adopting optical switching can not only achieve over 100 Tbit/s or even Pbit/s throughputs [5], but also dramatically reduce the power consumption [1], eliminate the high cost O/E/O conversions and thus make the switching operation independent of bit-rate and protocol.

Arrayed waveguide grating (AWG) is a very attractive passive device for constructing high-speed large-capacity WDM optical switches, because it can switch fast, is scalable to large size, consumes little power and has less noise accumulation [6]. An AWG-based optical switch construction was proposed in [7] based on a single stage AWG. Even with the full-range wavelength converters (FWCs), the design in [7] is still a blocking one. Recently, the non-blocking designs of AWG-based optical switches for both the wavelength-to-wavelength and wavelength-to-fiber request models were investigated in [8] when the dedicated limited-range wavelength converters (LWCs) is adopted. This work was further extended in [9] when the shared wavelength conversion is adopted. It is notable, however, only by the speed of wavelength conversion, which is in the order of nanoseconds.

A FWC can convert any one of the incoming wavelengths into any other one of the outgoing wavelengths.
that in the available AWG switch designs, the routing control is complex because they need either to solve the combinatorial puzzle problem [7] or to apply the searching-based algorithms [8, 9] to reduce or avoid blocking. The high routing control complexity of current AWG switch designs can not take the full advantages offered by the high-speed AWG, so it may significantly degrade the switch performance/throughput.

In this paper, we explore another branch of AWG-based switches with the most simple routing control, i.e. the self-routing AWG switches. Self-routing technique is an attractive choice for reducing the routing complexity and achieving the constant routing complexity. We will show how to guarantee in a self-routing AWG switch the nice nonblocking property for the both the wavelength-to-wavelength and wavelength-to-fiber request models, by also devising solutions for a critical function module required by our design.

The rest of this paper is organized as follows. Section II introduces the preliminaries and an attractive nonblocking design of AWG-based switches proposed in [8]. Section III presents the overall construction of our AWG-based switch with both the self-routing capability and nonblocking guarantee. Section IV provides two possible designs of a critical function module required in our switch design. In Section V, our construction is compared with available ones in terms of construction components and routing complexity. Finally, Section VI concludes this paper.

2 Preliminaries

The main notations to be used will be the same as that of [8], which motivates the work of this paper.

2.1 WDM Cross-Connect

A general “heterogeneous” WDM cross-connect (WXC) is illustrated in Fig. 1, with \( f_1 \) input and \( f_2 \) output fibers, each supporting \( w_1 \) and \( w_2 \) wavelengths, respectively, satisfying the condition \( f_1 w_1 = f_2 w_2 \). Without loss of generality, in this paper we just focus on the “homogeneous”

\[ \Lambda = \{ \lambda_0, \lambda_1, \ldots, \lambda_{w-1} \} \]

WXC constructions in which \( f = f_1 = f_2 \) and each fiber carries same set of \( w = w_1 = w_2 \) wavelengths. We use \( \Lambda = \{ \lambda_0, \lambda_1, \ldots, \lambda_{w-1} \} \) to denote the set of these \( w \) wavelengths and use \( F \) and \( F' \) to denote the set of input fibers and the set of output fibers, respectively. Let \( A \) and \( B \) be two wavelength subsets of \( \Lambda \), then the wavelength converter (WC) that converts any wavelength in \( A \) to any wavelength in \( B \) will be denoted by \( WC(A, B) \). Therefore a WC(\( A, A \)) is just a WFC. We also define \([i, j] \) as a subset of \((j - i)\) wavelengths \( \{ \lambda_i, \lambda_{i+1}, \ldots, \lambda_{j-1} \} \), and define \([0, j] = [j] \) for short.

In current AWG-based nonblocking WXC designs, two different request models have been mainly considered [8,9], namely the \((\lambda, F, \lambda', F')\) and \((\lambda, F, F')\) request models. In the \((\lambda, F, \lambda', F')\)-request model, an input signal carried on a wavelength \( \lambda \in \Lambda \) from an input fiber \( F \in F \) is destined for a specified wavelength \( \lambda' \in \Lambda \) on an output fiber \( F' \in F' \). As wavelength-to-wavelength switching is required under this request model, this model is suitable for circuit switching and quality of service (QoS) guarantees. In the \((\lambda, F, F')\)-request model, the only difference is that output wavelength of this request is not specified and can be any free wavelength in output fiber \( F' \in F' \). This model requests more general fiber-to-fiber switching and is more suitable for optical burst/packet switching.

2.2 Arrayed Waveguide Grating Routers

The arrayed waveguide grating router (AWGR) is an attractive passive wavelength routing device that consumes almost no power, has less noise accumulation and can switch very fast (only through wavelength conversion) [6]. In an AWGR, the routing of an input signal is solely determined by its wavelength and input port address. For a \( d \times d \) AWGR illustrated in Fig. 2, an incoming optical signal carried on the wavelength \( \lambda_m \in [d] \) in the \( i \)-th input will always be switched to a given output port \( k \) on the same wavelength, where \( k \) is given by

\[ k = (m - i + d) \mod d \] (1)

where \( m \geq 0 \) and \( i, k < d \). From the above equation we can easily see that in an AWGR a signal in any input port can actually reach any output port by properly controlling its wavelength \( \lambda_m \).
2.3 A Nonblocking AWG-based Switches

By emulating the well-known Clos switch architecture [10], a novel AWG-based switch design was proposed in [8] to provide the strictly nonblocking (SNB) guarantee for both the \((\lambda, F, F', \lambda')\) and \((\lambda, F, F')\) request models. One such SNB design is illustrated in Fig. 3 for the case when \(f = 2\) and \(w = 8\). We can see from the Fig. 3 that this design consists of limited-range wavelength converters (LWCs) and two-stage of AWGRs, where the second-stage of AWGRs just corresponds to the middle stage of a Clos switch. It is notable that in the above Clos-like design of AWGR-based switch, multiple routing paths are available for each input-output pair. For the example shown in Fig. 3, all the three paths for the request \((\lambda_1, F_0, \lambda_1, F_0)\) are highlighted. Since the routing path for a request is not fixed and must be selected among one of \(n\) second-stage AWGRs (here \(n = 3\) and \(n\) is also the size of first stage AWGR [8]), so the worst routing complexity can be as high as \(O(nfw)\) for both request models. This routing complexity of above designs increases with both the switch size \(fw\) and parameter \(n\). This high routing control complexity will not only significantly degrade the performance/throughput of current AGW-based switch designs, but also make the all-optical implementation impractical for the future massive WDM switches.

3 A New Self-routing and Nonblocking Design of AWGR-based Switch

In this section, we propose a self-routing design of AWG-based switch that has the constant routing complexity and can still provide the nonblocking guarantee for both the \((\lambda, F, F', \lambda')\) and \((\lambda, F, F')\) request models.

3.1 Construction Overview

The main idea of our proposed AWG switch design is inspired by the Spanke switch architecture [11], which is well-known as a self-routing and nonblocking architecture. For an AWG-based switch that supports \(f = 2\) input (output) fibers with \(w = 8\) wavelengths each, one sample construction of the proposed self-routing design is illustrated in Fig.4. In the proposed construction, the \(w\) wavelengths of each fiber are partitioned into \(b\) consecutive bands with size \(n\) each. All the \(\lambda_s\) in one band, each controlled by a WC(\([fb]\), \(\Lambda\)), are inputs to an \(n \times n\) special module in the first stage, referred to as the “wavelength multiplexing switch” (WMS). The second stage of the design consists of \(n\) AWGRs of size \(fb \times fb\), followed by a WC(\([fb]\), \(\Lambda\)) in each output port. All the WMSs and AWGRs in the design are continuously numbered from WMS\(_0\) to WMS\(_{fb-1}\) and from AWGR\(_0\) to AWGR\(_{fb-1}\), respectively.

In the proposed design, the main function of the special WMS module is to guarantee that any set of distinct wavelengths at any set of its distinct input ports can be simultaneously routed to any common output port. This function also implies that a given wavelength at a given input port can be freely routed to any output port. One possible design of WMS will be introduced in Section IV to provide the above function. We should note that the function requirement of WMS is much stronger than its AWGR counterpart, since in AWG a given wavelength at a given input port can only be routed to a fixed output port. The connectivity difference between WMS and AGWR is further illustrated in Fig. 5.
It is worth noting that our two-stage design makes it possible to control the overall complexity of the WMS module, since we can properly select its size ($n$) to make it suitable to the available technology. A single-stage solution would require necessarily a single WMS whose dimension ($f_w$) is only determined by external parameters.

In addition to the new and more powerful WMS, the new switch design also explores both the WDM property of the central links and the splitting function of AWGRs, since in our design each central link now can simultaneously multiplex wavelengths and each AWGR at second stage can automatically splits these multiple WDM signals carried in the central links in a same way as a passive splitter (please refer to Fig. 4 for the routing of two connections ($F_1, \lambda_6, F_0, \lambda_5$) and ($F_1, \lambda_4, F_0, \lambda_7$)). These nice properties, as far as we know, were not fully explored in available SNB designs of AWG-based switches [8, 9].

In the next two subsections, we will show that based on the new WMS module and thanks to the above two properties, our design is able to provide both the self-routing and nonblocking (SNB) guarantees for the $(\lambda, F, \lambda_\prime, F_\prime)$ and $(\lambda, F, F_\prime)$ requests.

### 3.2 Self-routing Guarantee

In this section, we will show that the proposed design has the self-routing capability for $(\lambda, F, \lambda_\prime, F_\prime)$-request model i.e. it can determine a unique path (i.e., lightpath) for such a request based only on its input address ($\lambda, F$) and output address ($\lambda_\prime, F_\prime$).

**Theorem 3.1.** The proposed design provides self-routing capability for any $(\lambda, F, \lambda_\prime, F_\prime)$ request.

**Proof.** For a tagged request in the form of $(\lambda_p, F_q, \lambda_{p'}, F_{q'})$, we will first prove that only one unique path is available for it and then show how to determine the path based on its input and output addresses only.

Suppose that the input port of $(\lambda_p, F_q)$ is associated with WMS$_i$ in the first stage and the $(\lambda_{p'}, F_{q'})$ is associated with the output port $k$ of AWGR$_j$ in the second stage, then the connection pattern between WMS$_i$ and all $n$ AWGRs (including the AWGR$_j$) is illustrated in Fig. 6. We can see easily from the Figure that the only central link between WMS$_i$ and AWGR$_j$ is the one that connects the $j$-th output of WMS$_i$ to the $i$-th input of AWGR$_j$. Of course, to prove that the tagged request only unique path is available between WMS$_i$ and AWGR$_j$, we need to show that the wavelength that can be used for it is also unique. Notice that from the $i$-th input to the destined $k$-th output of AWGR$_j$, only a unique wavelength (and thus a unique path) is available due to the wavelength-based switching property of AWGR. Suppose this unique wavelength is $\lambda_m$. Since no wavelength conversion capability is available between the WMS stage and AWGR stage, so for the tagged request only the wavelength (and thus the only path) that can be used between WMS$_i$ and AWGR$_j$ is just $\lambda_m$. Thus, for the tagged request only a unique path is available through the proposed switch design.

The routing indices $i, j$ and $k$ for the tagged request can be easily determined from the architecture of proposed design. For example, the index $i$ is defined as

$$i = bq + \lfloor p/n \rfloor \quad (2)$$

Similarly, let $n' = fb$ and $b' = w/fb$, so that $j$ will be defined as

$$j = b'q + \lfloor p'/n' \rfloor \quad (3)$$

The index $k$ is then uniquely defined by $j$ and $\lambda_{p'}$ (please refer to Fig. 4). From the indices $i$ and $k$, the wavelength index $m$ of the tagged request will be uniquely determined by the following formula based on the routing property of AWGR in (1)

$$m = (i + k) \mod (fb) \quad (4)$$

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**Figure 5.** Connectivity comparison between WMS and AWGR.

**Figure 6.** Connection pattern between WMS, and AWGRs.
From the above proof we can see that to route a connection \((\lambda_p, F_p, \lambda_q, F_q)\), it first needs to go through the first stage LWC, which converts its wavelength \(\lambda_p\) into \(\lambda_{m_i}\) and routes it to the WMS, based on the architecture of the proposed design. Based on its output address \((\lambda_{p'}, F_{p'})\), the WMS routes it to AWGR, through the unique link between them. The AWGR then automatically route this signal to its destined output port \(k\) based on its input port number \(i\) and its wavelength \(\lambda_{m_i}\). Finally, this signal is converted to its destined wavelength \(\lambda_{p'}\) by the second stage LWC. For example, for two requests \((F_1, \lambda_5, F_0, \lambda_3)\) and \((F_1, \lambda_4, F_0, \lambda_7)\), their routing is illustrated in Fig. 4.

It is notable that the routing complexity of any \((\lambda, F, \lambda', F')\) request is just \(O(1)\), since its route is simply determined by Equations (2),(3) and (4) only.

### 3.3 Nonblocking Guarantee

In this section, we further show that the proposed design is also nonblocking (strictly nonblocking) for wavelength-to-wavelength request model.

**Theorem 3.2.** The proposed construction is nonblocking under \((\lambda, F, \lambda', F')\)-request model.

**Proof.** To guarantee the nonblocking property under the \((\lambda, F, \lambda', F')\) model, we just need to show that for any two different \((\lambda, F, \lambda', F')\) requests (with different input address \((\lambda, F)\) and also different output address \((\lambda', F')\)), blocking will never happen along their paths. First, blocking can not happen at their input/output ports, since each \((\lambda, F)\) pair (correspondingly \((\lambda', F')\) pair) has its dedicated input port (output port) as defined by the switch architecture itself. Second, blocking in a WMS module can not happen between these two requests, i.e., they can not be routed to the same output of the WMS on a same wavelength. Otherwise, these two requests will be forwarded to a common input of a AWGR on the the same wavelength and will be finally routed to the same output address (notice the output addresses of these two requests can not be same). Finally, blocking can not happen at the AWGR stage, since two signals of same wavelength can neither be routed to a common input of an AWGR as guaranteed by the preceding WMS stage nor routed to a common output port as assured by the routing property (1) of AWGR.

We can see easily from above proof that for any two different \((\lambda, F, \lambda', F')\) requests, their paths never share any common link/wavelength pair, so the routing of a new request is completely independent from other connections. Thus, the proposed design actually provides the strictly non-blocking guarantee for \((\lambda, F, \lambda', F')\) request.

### 4 Wavelength Multiplexing Switch

In this section, we propose the design of the WMS (wavelength multiplexing switch) module adopted in our switch architecture.

#### 4.1 Splitter-based Design

The combination of optical splitter and semiconductor optical amplifier (SOA) is an attractive approach to building high-speed but small size switch, because a connection can be switched ON or OFF in nanosecond by using only single SOA [14,15]. A \(n \times n\) WMS design based on the splitter and SOA is shown in Fig. 7, where an incoming signal is split into \(n\) signals by an input-side splitter. The switch function is then controlled by the SOA, since each signal is routed to an output only when the corresponding SOA is activated, otherwise this signal will be dropped (blocked). It is notable that the above splitter-based construction of WMS essentially supports the multicast transmission capability. How to explore this capability to design the self-routing and multicast optical switch remains to be explored further.

### 5 Comparison with Available WXC Const.

In this section, the proposed switch design will be compared with the available AWGR-based SNB design [8] in terms of both hardware requirements and routing control complexities. The comparison results are summarized in Table 1, where \(x \otimes y\) means \(x\) elements (AWGR or WMS) of size \(y \times y\) each, and in Table 2. For the hardware requirement, we can see from Table 1 that the LWC complexity of available AWGR-based SNB design in [8] is at least 1.5 times as that of the new design given that \(w \gg b\) in normal cases, while its AWGR complexity is about 3 times as that of the new one. Although the new design requires the WMSs with complexity \(fb \otimes n\), its overall construction
complexity can be even lower than the available design if an efficient design of WMS is adopted. For routing control complexity, the proposed self-routing design clearly outperforms the available one (see Table 2). Since in the AWGR-based SNB design [8], the sequential searching process may result in a worst complexity as high as $O(nfw)$, while the proposed design can always guarantee a constant routing complexity under both $(\lambda, F, \lambda', F')$ and $(\lambda, F, F')$ request models.

6 Conclusion

In this paper, we have proposed a self-routing and also strict nonblocking (SNB) design of optical switch for both wavelength-to-wavelength and wavelength-to-fiber request models. We have showed that despite its self-routing and nonblocking guarantees, the overall construction complexity of the proposed design can be even lower than the available AWG-based SNB switch design. One possible future work is to find a more cost effective design for the wavelength multiplexing switch (WMS) module adopted in our construction.

References


