

Single-layer multigranular optical cross-connect architecture with conversion capability and enhanced flexibility

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The rapid advances in WDM technology are expected to bring about tremendous growth in the size of optical cross connects (OXC). In this context, multigranular OXCs (MG-OXCs) have been suggested as a means of reducing the amount of equipment required. Here we expand the concept of MG-OXCs to include optical packet granularity and review the key building blocks for the advent of MG-OXCs. A single-layer MG-OXC is suggested that offers enhanced flexibility with respect to other single-layer concepts, conversion capability, and good physical performance. Concatenation performance is analytically investigated. © 2006 Optical Society of America

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1. Introduction

Today, the WDM transport layer is migrating from a set of simple transmission links to an intelligent optical network with optical add-drop (OAD) and cross-connect nodes (OXCs) for routing and management of the optical bandwidth with low complexity and cost [1]. In future WDM networks, thousands of wavelengths may be deployed to fully exploit the available fiber spectrum [2–4]. As the size of OADs and OXCs is increasing, together with the associated cost, complexity, and control requirements, optical switching may appear in the form of multigranular OXCs (MG-OXCs) that will provide switching at wavelength (WXC) and waveband level (WBXC) and support a wide range of granularity [4–6]. At the networking level, specific bands of wavelengths may be required to provide capacity between specific network nodes. Meanwhile the ever-increasing demand for flexibility and capacity will encourage the introduction of optical burst and packet switching for some of the wavelength channels [7].

In Refs. [3,8] a MG-OXC is suggested on the basis that only a fraction of the input traffic needs to be switched at any particular node, while the rest just bypass the node. Waveband switching has attracted much attention by virtue of its practical importance in reducing the number of switch ports and associated cost and control complexity. The concept of waveband switching is to group a number of wavelengths as a band, which will be switched as an entity (waveband) through a single switch port. In this way, the port count of a switch may decrease, but the size of the digital cross-connect may be reduced as well [3,8]. The approach is based on three levels of granularity, namely, wavelength, waveband, and fiber switching. This enables the capacity of the network to increase while minimizing the complexity and cost of the node. In the scenario suggested here, an additional level of subwavelength granularity is added, i.e., optical packet or burst switching [7]. Neglecting the fiber switch, as

shown in Fig. 1(a), the MG-OXC has three layers (single-layer and multilayer architectures are defined as in Ref. [4]), comprising a WBXC (with local OAD, to the WXC or to OPS), a WXC (with local OAD or to the OPS), and an OPS (with local OAD). This is a multilayer MG-OXC. A single-layer MG-OXC is illustrated in Fig. 1(b). Clearly the first offers more flexibility, as the number of wavelength channels to be dropped to the second layer is not fixed, while in the single layer the use of the demultiplexer imposes limited flexibility. However, in Fig. 1(a) a large number of extra ports are required in each layer for adding and dropping wavelengths between the layers. Hence the second requires fewer components and simpler control.

Ideally, the features of MG-OXC are similar to those of the OXC and should include the following [9–11]:

- Switching capability of any channel to any unused channel (WB, W, or packet) in a strictly or reconfigurable nonblocking fashion.
- Variable switching and add-drop percentage up to 100% according to the scenario. Specifically for the MG-OXC this also implies variable reconfigurability between the layers of the MG-OXC.
- Support virtual wavelength/waveband paths through wavelength/waveband assignment capability—this means that they have both wavelength and waveband conversion capability.

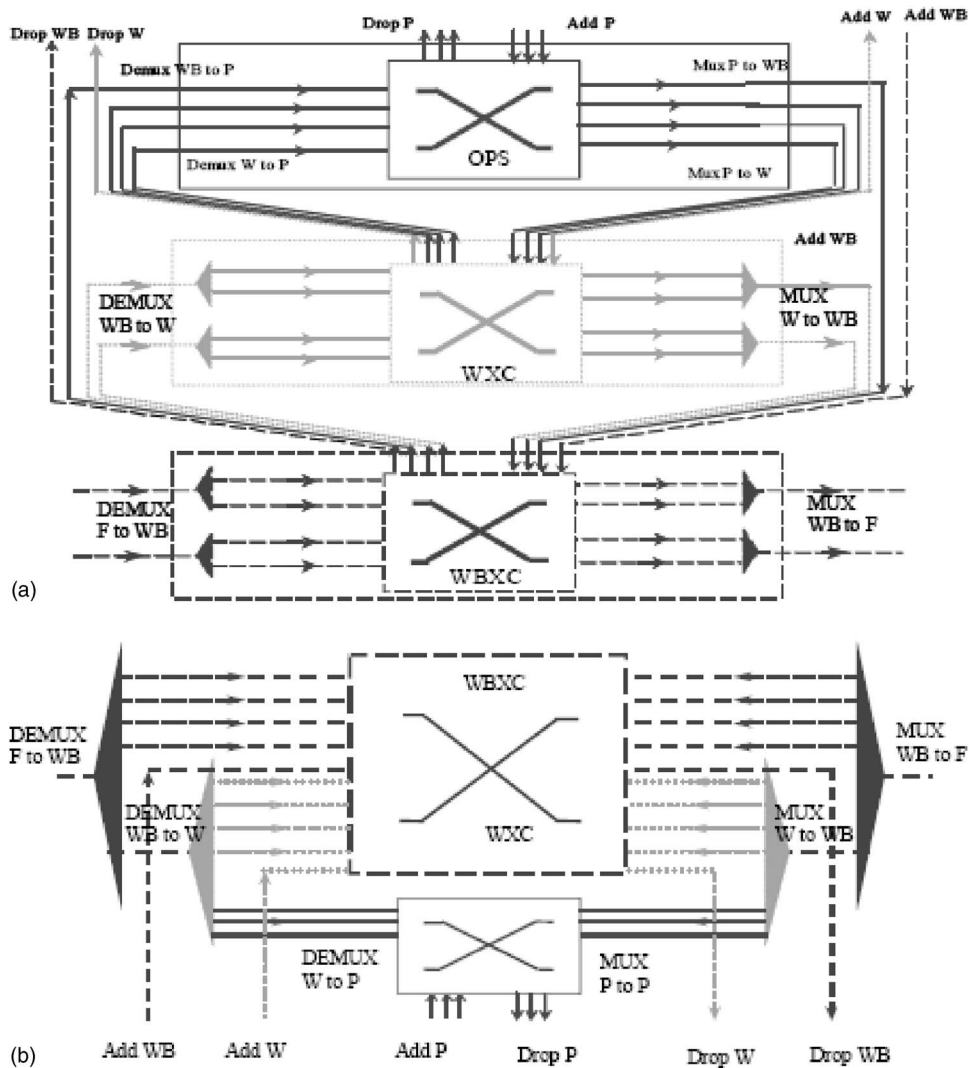


Fig. 1. (a) MG-OXC architecture. Dropped fibers (F) are demultiplexed in wavebands (WB). These are switched as an entity and then either dropped to the WXC or to the OPS or dropped locally. Wavelengths (W) in the WXC are either switched at the WXC or dropped to the OPS or locally. (b) Single-layer OXC where WB are directly switched either as an entity or dropped to the WXC where W are switched or to the OPS, etc. [4,8].

- Dynamic reconfiguration supporting fast switching speed (\sim ms for W and WB nsec for packets)
- Transparency or bit-rate tailored configuration.
- Scaleable architecture in a modular fashion for upgradeability issues.
- Minimum physical performance degradation and ideally uniform for WB, W, and packets.
- Strictly nonblocking connectivity between input and output ports.
- Span protection and mesh restoration capabilities.
- Minimum cost and simplified control.

Although many architectures have been discussed in terms of their switch matrix, the exact available technology for the proposed schemes remains to be investigated. Usually MG-OXC switch architectures are developed on simple OXC counterparts, so special requirements are not considered, such as the requirement that add-drop should be accommodated between WBXC and WXC for multilayer schemes or band-demultiplexers for single-layer ones. Furthermore, wavelength conversion is a function that is very significant for optical networks, but the immaturity of waveband conversion technologies and/or the poor physical performance of the available techniques has imposed the trend of developing WBXC without conversion capabilities. The possibility of converting channels at the wavelength layer evidently eliminates the argument for low component count. Here we discuss the requirements for band conversion and enabling technology and we propose a MG-OXC architecture in detail that offers a trade-off between good physical performance and reduced component count.

2. Key Building Blocks for MG-OXC: Converters, Regenerators, and Switches

Waveband Conversion. Optical wavelength conversion is required within an OXC to maximize network flexibility, reduce network blocking, and improve restoration performance. For the MG-OXC, conversion at both the wavelength and waveband level is required. At the same time, waveband converters have been proposed for replacing a number of wavelength converters in a node. Multiwavelength processing in a single device has been suggested as a way of reducing the number of components, the power consumption, and thus the cost of a node. In addition, controlling one rather than a number of components is more efficient and hence preferable; for this reason waveband conversion is desirable even in networks that do not support banding [12], as the introduction of functions such as wavelength conversion will be determined by network economics.

The suitability of optical waveband converters for future networks will be judged upon specific criteria that these must fulfil. In particular, modules will ideally and simultaneously have to be compact, operate at low optical and electrical powers with high dynamic range, be polarization insensitive, have complete transparency to bit rate (>100 Gbit/s) and format, induce minimal power penalty (small chirp, amplitude distortion and low extinction ratio degradation, and large OSNR) and minimal interference between channels, have uniform effect on all channels of the band, provide regeneration, offer wide conversion bandwidth, and provide arbitrary mapping between input and converted signals.

Simultaneous conversion of many wavelengths is a very distinctive feature of wave-mixing techniques and of four-wave mixing (FWM) in particular [12]. Experimental demonstrations of waveband conversion based on FWM in optical fiber have been reported [13], but wide tunability and the large lengths of nonlinear fiber that are required do not make this technique attractive for practical implementation. Wave mixing techniques other than FWM have been proposed in the literature for waveband conversion. Among these, differential frequency generation (DFG) offers numerous unique advantages such as wide tunability [14], bandwidth and format transparent conversion [15] without spontaneous emission, and operation with a pump out of the band of the involved signals. Since DFG does not take place in a saturable medium, its performance is not limited by cross-talk effects [16]. However, dual-pump FWM in an integrated SOA has been proven to be very promising in terms of performance in system applications [17], especially when high bit rates are used, and hence it is preferred in this paper.

Because most waveband conversion techniques have poor efficiency, multiwavelength regeneration is popular. Two interesting techniques in terms of operation that

offer performance improvement during operation in a multiwavelength mode are discussed here. The first is based on self-phase-modulation (SPM), and the scheme involves reshaping of the pulses [18]. The second technique is based on the use of heterogeneously broadened gain of quantum dots [19].

Switches. A variety of optical switch fabrics have been developed [1,20] that exhibit different performance. Switching time is a very significant feature that dictates the overall switching time of the node. There are other switch fabric technologies that are under development; however, for single-layer MG-OXCs, the fabric should be able to simultaneously support switching of switch W, WB, and packets. In that sense the variety is limited to micromechanical systems (MEMS) [21], semiconductor optical amplifier gates [8], or the combination of a converter with an AWG [12].

A number of OXC architectures have been reported in the literature, depending on the number of ports required. To build high port count nodes, the simplest solution is based on a central switch fabric, which can potentially support a high port count, like the crossbar switch. Potential candidates for high port count OXC are 3-D MEMS [1]. Most of the other, more mature fabrics can provide smaller matrices, typically 32×32 . Therefore, various multistage optical switch structures have been suggested. Among those the wavelength selective switch architecture and broadcast and select are the most interesting [10].

This paper proposes a new MG-OXC architecture that relies on a set of waveband converters followed by a passive wavelength routing device, based on arrayed waveguide grating (AWG) technology. The configuration uses an input WBC layer followed by an AWG to enable optical switching and an output single wavelength conversion (SWC) layer for regeneration [22]. This is because multi-wavelength regeneration is still immature. The waveband routed WXC architecture that have been suggested in [12] can be used as a WBXC. The combination of the WXC and WBXC form a single-layer MG-OXC with enhanced flexibility and wavelength assignment capabilities. The enhanced flexibility stems from the fact that no band demultiplexers are required as demultiplexing of the bands is performed by the AWG itself.

3. Single-Layer MG-OXC with Enhanced Flexibility

In the literature, there are two suggested kinds of MG-OXC: multilayer and single layer (Fig. 1). Here, a single-layer MG-OXC with enhanced flexibility is suggested. Assume a node that serves N incoming fibers, each carrying m fixed number of wavebands with k fixed number of wavelengths in each band. All $n = N \times m \times k$ channels are switched through the OXC. Figure 2(a) shows the schematic diagram of an $N \times N$ fiber MG-OXC based on the proposed design [12]. This scheme relies on wavelength routing, where optical signals are switched to the appropriate output ports through waveband converters (WBCs) and an $M \times M$ AWG router. Each input fiber carries a number of wavelengths that are demultiplexed into bands, through a band demultiplexer (BDMUX). The proposed architecture utilizes grouping of wavelengths in bands to perform routing of the input wavelength channels to the appropriate output ports of the OXC but does not necessarily impose a banded wavelength channel plan at the transport network level [12]. Hence the added flexibility stems from the fact that even when treated in bands, wavelengths are switched separately. This means that the general architecture can be utilized as either a WBXC or a WXC.

When the architecture is used as a WXC, special measures have to be taken to avoid blocking, and the issues have been discussed in Ref. [12]. One of these is the requirement for additional AWG output ports (see Appendix A). These are coupled in a predetermined fashion through passive coupling so that nonblocking switching with a minimum number of components can be performed. At the output of the AWG, SWCs are used for regeneration and wavelength assignment. These can be based on one of the available regeneration techniques. In the example that is investigated here the WBCs are based on FWM-tunable WBC technology and the SWCs on cross-phase modulation. In that way, the architecture makes a compromise between offering conversion capabilities, good physical performance with available technology, and converting at the band level. In Appendix A an example is given to elaborate on the above. For the OPS, the experimental configuration has been studied in Ref. [22]. In the same figure [Fig. 2(b)], the uni-granular OXC based on the same switching technology is shown for comparison.

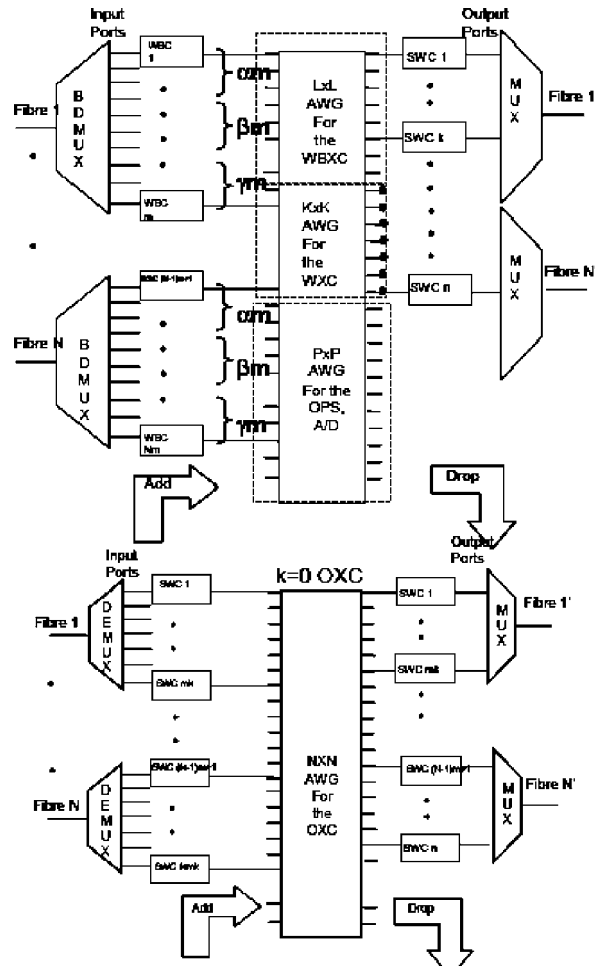


Fig. 2. (a) Single-layer MG-OXC with the two main levels (WBXC and OXC) and a third for an OPS or OAD. The WXC part of the AWG has more output ports that are coupled in a predetermined fashion. (b) a uni-granular OXC for comparison purposes. Note: band demultiplexer (BDMUX)–waveband converter (WBC)–single wavelength converter (SWC).

This single-layer MG-OXC comprises three layers as in Fig. 2. It is aimed at a network that supports a fixed number of wavebands, with a fixed number of consecutive wavelengths in each waveband [12]. This is a special case for all possible variations presented in Ref. [4]. The suggested switch has all the merits of the single-layer switch (i.e., reduced component count; simple architecture to implement, configure, and control) but also added flexibility with respect to the single-layer switch, shown in Fig. 1, owing to the absence of a wavelength demultiplexer in any of the layers. To elaborate on the last argument, it should be noted that the wavelength demultiplexer [see Fig. 1(b)] determines which specific wavelengths can be routed to a specific layer. This means that in the single-layer configuration of Fig. 1, only predetermined wavebands can be “dropped” to the WXC and switched as wavelength channels. In the MG-OXC of Fig. 2, however, no wavebands are differentiated by the others, and they have an equal chance to be routed to any of the layers of the MG-OXC. This represents the added flexibility of this single-layer MG-OXC.

Furthermore the design proposed here gives a more uniform impairment of the routed channels, independent of the layer they will be routed into, as the physical routes are very similar. Finally, some ports of this switch are serving the OAD. In a multilayer switch, each of the layers would dedicate some ports to OAD. In this way the MG-OXC of Fig. 2 is more efficient in terms of port count. Another merit of the architecture is that it uses a very fast switch fabric (\sim nsec switching time) for all levels of granularity. MEMS, for example, would result in a slow switch fabric for such a single-layer MG-OXC.

In Fig. 2 the MG-OXC supports three levels of granularity corresponding to the three sections: a WBXC, a WXC, and a third section for OPS and add-drop (fiber

switching is assumed to be done separately). In this section the discussion is on the WBXC and WXC and can be expanded to the OPS. The WXC will follow the design of the WXC of Ref. [12]. The WBXC section design is straightforward, and no special considerations are taken for the AWG port count and the like. A common AWG for the three layers is used, and the issues of AWG port count, coupled output ports, and number of components are similar to those already discussed in Ref. [12] and shown in Appendix A.

Assume N fibers need to have their m bands demultiplexed. All $n=N \times m \times k$ channels are demultiplexed in bands of k wavelengths. Each band is converted to an appropriate set of wavelengths to be routed either to the upper part of the MG-OXC (WBXC), to the middle (WXC), or to the lower part (OPS, etc.). Then it is routed through the AWG that now comprises $M \times M$ output ports. This $M \times M$ will include the $L \times L$ for the WBC, the $K \times K$ for the WXC and $P \times P$ for the channels that will be dropped locally or to the packet switch, and $M=L+P+K$. The L AWG outputs are directly connected to the output SWC, while the K AWG output ports are coupled in sets before entering the output SWC [23], which is necessary to ensure that the switch is nonblocking (Appendix A). Any of the $N \times m$ bands can be either switched as an entity or as a wavelength; however, the number of bands to be switched as an entity should be predetermined. This is defined as limited reconfigurability [4]. Note that for $k=1$ the case collapses to the uni-granular OXC of Fig. 2(b).

To clarify the above, it is assumed that after appropriate demultiplexing the $m \times k$ channels from each of the N fibers, a percentage α of those will be switched as entities, a percentage β requests to be routed as wavelengths, and a percentage γ to be dropped locally (or to the packet switch). These percentages result from network planning analysis [4] and are directly related to the number of input AWG ports $M=P+K+L$ required for the routing and in turn to the number of converters. The constraint is that the number of SWC plus WBC must be kept to a minimum, which means less than the number of converters in a WXC, i.e., $2(\alpha+\beta+\gamma)n$. Evidently, if the number of converters grows larger than this number, waveband switching ceases to be beneficial. This is equivalent to the argument that the ports of a MG-OXC should be less than the ports of the WXC [12].

From Fig. 3 it is evident that as k grows, the converter count drops significantly but the AWG port count rises extremely. Furthermore, in the case where $\alpha+\beta+\gamma>1$ is required either for reconfigurability purposes or for traffic growth planning, the number of converters grows but is always less than the equivalent $k=1$ case. To be specific, let us assume the case where $k=2$. If only $\alpha \times n$ ($\alpha=0.2$) are required for waveband routing, 24 channels will remain in bands and 24 AWG outputs will be required for the WBXC part of the MG-OXC (i.e., $L=24$). If 72 channels ($\beta=0.6$) need to be routed in the WXC, then $M=5113$. The total number of converters is given by the formula $Z=(\alpha+\beta+\gamma)(n/k+n)=180$. The number is reduced, but the large number AWG output ports may not allow this scheme to be feasible. However, if only a small percentage of bands must be dropped into the WXC, as is the case with $\beta=0.6$, the total number of the AWG output ports remains at a reasonable level ($K=553$) and the number of wavelength converters is still reduced. It should be noted here that other than the reduction of converters, the elimination of demultiplexers—which would be of the order of $\beta n/k$ in any single-layer MG-OXC—would significantly reduce cost.

In conclusion, a single-layer MG-OXC architecture is proposed. Here the efficiency of the architecture was discussed in terms of flexibility, reconfigurability, and feasibility. The architecture is more flexible than that of any other single-layer MG-OXC, since any waveband can be routed as a band or as wavelengths. It has limited reconfigurability, however, as the number of wavebands to be routed as wavelengths is fixed. The MG-OXC offers conversion capabilities. The architecture was compared with the wavelength OXC in terms of component count and is beneficial for a network that has a large number of express channels (high β) and many wavelengths per band, hence suitable for a core network with 60% express traffic [24].

4. Physical Performance of a Single-Layer MG-OXC

For a complete evaluation of the suggested architecture, one has to judge the design considerations that stem from the available technology. As mentioned above, the deployment of a WBC imposes requirements on the design of the switch fabric, mainly

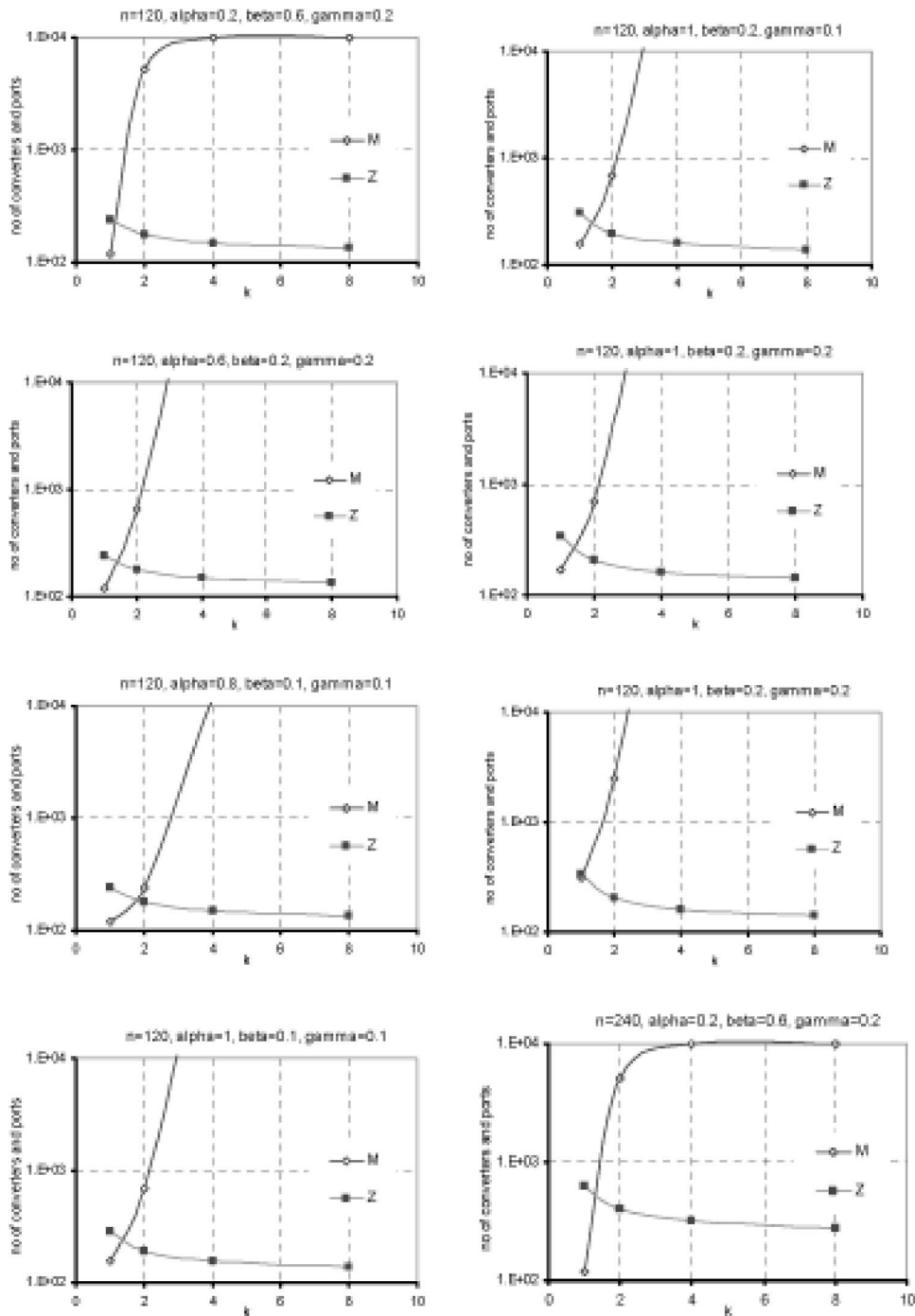


Fig. 3. Number of converters or AWG ports with respect to k for different cases of n , combinations of α, β, γ as indicated in the keys.

because available waveband conversion technology allows conversion of a band of consecutive wavelengths only to consecutive wavelengths; moreover, band inversion is realized. For widely tunable WBC, we use dual-pump FWM in a fixed input-tunable output configuration, where one pump is fixed and the second is tunable and is used in an out-of-band routing scheme [17]. The second pump is out of the band of the input grid of wavelengths, so input signals and output products are spectrally separated. A significant benefit of this is that the routing wavelengths can be chosen such that only down conversion is required. Hence, OSNR enhancement is achieved if the SOA is chosen such that the fixed input waveband lies close to the SOA bandgap [17]. A final benefit is that suppression of the pumps can be facilitated by the AWG. So out-of-band FWM routing is beneficial for the design of waveband routing schemes as far

as OSNR, cross talk and interference is concerned, but it will be limited by the number of routing wavelengths limited by the bandwidth of the WBC and the AWG dimensionality.

The dimensionality of the AWG is associated with the number of routing wavelengths required to have a strictly nonblocking switch. The cross talk imposed on each channel in the AWG, however, is not related to its size but rather to the number of signals that coexist in the AWG, which equals the number of signals n in the node. The output SWC is expected to provide regeneration at the OXC output and significantly enhance the concatenation performance of the node.

In Ref. [25] an analytical model for the concatenation performance of a waveband routed switch was developed. Some assumptions for the model are shown in Appendix A. Here the model is used in order to understand the cascability versus the scalability performance. The bit-error rate (BER) of a signal that is concatenated through eight nodes is calculated with respect to the signal power for four different cases that correspond to the cases of Table 1. All signal parameters and system parameters are outlined in Ref. [25]. The BERs are shown in Fig. 4. The nodes are assumed to operate for $k=2$ and $n=2$; $k=2$ and $n=120$; $k=4$ and $n=4$; $k=4$ and $n=120$. These cases represent most of the cases shown in Fig. 3 as the performance of the node is affected mainly by the number of channels that coexist in the node and the number k . For example, whether the AWG has 5161 or 659 ports does not affect the cross-talk effect, which is of the order of 120 channels (240×240 AWGs have been reported in the literature; for higher port count AWGs, multistage AWGs have been reported Ref. [13]).

To be more precise, increasing the number of overall channels in the system affects the EDFA gain, the cross talk, the interference, and the AWG losses. So the difference between the performance of $k=2$, $n=2$ and $k=2$, $n=120$ is attributed to those effects. Increasing k , for example, affects the performance of the WBC. It is obvious that increasing k in a band affects irreversibly the performance regardless the use of regenerators.

Increasing the α , β , and γ increases the number of AWG ports and hence the AWG losses. The effect of such an increase is not detrimental. It should be noted here that the models presented in Ref. [25] do not take into account the wavelength dependence of the WBC and SWC and hence cannot decide on the uniformity of the performance of all the channels. However, in this paper we investigated only available technology that has been experimentally investigated [12,13,22] and not the possibility of using regenerative waveband converters, for example.

In conclusion, the performance of the suggested MG-OXC architecture has been investigated with the assistance of an analytical model. It is evident that although a large number of wavelengths in a band is beneficial for the MG-OXC, it is not beneficial for its feasibility. A fine trade-off between cost effectiveness and performance is $k=2$, independent of the sum $\alpha+\beta+\gamma$.

5. Conclusions

This paper has presented and investigated a new, to our knowledge, MG-OXC architecture that supports wavelength and/or waveband switching granularity with reduced component requirements and conversion capability. In terms of technology, the architecture comprises WBCs using FWM in SOAs, an AWG wavelength router, and SWCs using XPM in SOAs. This is widely available and is a good compromise between number of components (if only waveband conversion was used) and performance. The architecture is used as a WXC and as a WBXC. Hence a WXC and WBXC can be combined to form a single-layer MG-OXC. The design of the WXC is more

Table 1. Examples of K , P , and M Values with Respect to k , m , and n

k	m	N	n	α	β	γ	L	K	P	M	Z
1	60	2	120	0.2	0.6	0.2	n.a.	120	–	120	240
2	30	2	120	0.2	0.6	0.2	24	5113	24	5161	180
2	30	2	120	0.6	0.2	0.2	72	553	24	659	180
2	30	2	120	0.8	0.2	0.2	96	553	24	673	216
4	15	2	120	0.2	0.6	0.6	24	>10000	24	>10000	150
4	15	2	120	0.6	0.2	0.2	72	>10000	24	>10000	150

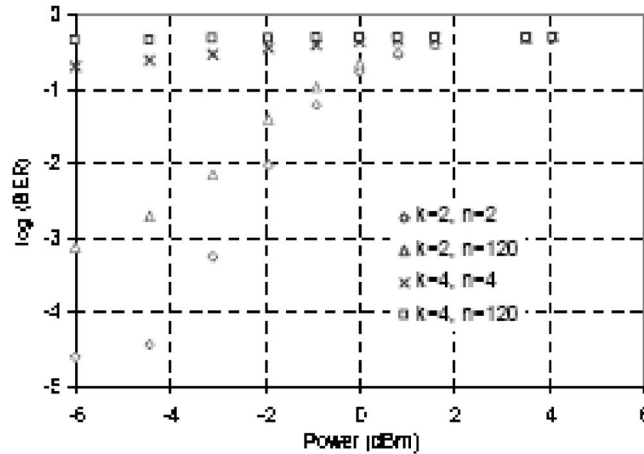


Fig. 4. BER of a signal after eight cascaded nodes for the cases noted in the key and $\alpha + \beta + \gamma = 1$.

stringent as far as scalability is concerned. Scalability analysis for the proposed architecture is performed taking into account existing technology limitations. Considering the immaturity of waveband regeneration technology, the architecture provides a trade-off between reduced component count and single wavelength regeneration capability. However, for feasible configurations the network should be such that β is very high (number of AWG ports remains reasonable) and that $k=2$ for good physical performance.

To judge whether this single-layer MG-OXC is a potential candidate for a network requires assessment against the checklist mentioned in the introduction. The design satisfies all the requirements for low cost and power consumption. The architecture is dynamically reconfigurable with low switching time, limited only by the tuning speed of filters since the fabric can be switched in \sim nsec; however, it incorporates wavelength converters and thus its transparency is limited. The architecture offers switching with strictly nonblocking capability as any wavelength channel can be switched to any unused wavelength; however, the reconfigurability is limited as the switching percentage is less than 100% between the layers of the MG-OXC. Scalability of the system is limited by the available AWG technology unless specific architectures are utilized, as, for example, multistage AWGs. The architecture has good performance and is almost uniform among the channels of the same band, but also between the wavebands and wavelengths in this architecture, though it has the potential for better performance if waveband regeneration is used.

Appendix A

1. Example of 2×2 WXC

The main consideration in scaling an $N \times N$ WXC architecture is the number of wavelengths per waveband, k . The number of AWG output ports M required for an optimized design and the number of coupled output ports ($\lfloor M/N \rfloor$), which limit the scalability are both dependent on k for a specific number of channels n . The minimum number of output ports M for the optimized architecture is given by $M = n! / (n-k)! + k - 1$.

A 2×2 fiber WXC with each fiber supporting two wavelength channels ($k=2$, $n=4$) as discussed in Ref. [12] is shown in Fig. 5 below (input port 1: λ_1 and λ_2 input port 2: λ_3 and λ_4). In this specific example the four input channels need to be routed to four discrete output ports (identified by the output wavelengths λ_1 , λ_2 , λ_3 , and λ_4) in any possible combination.

This design imposes the requirement for a minimum of 13 AWG ports and 14 wavelengths. To achieve this, the output AWG ports are appropriately coupled into groups of three, while one group of four coupled ports is required. The waveband entering the node through the first input port must be converted to two consecutive wavelengths of the wavelengths noted in plain numbers in the figure (numbers 5–17). The channels entering the node through input port 2 need to be converted to two consecutive wavelengths of the wavelengths marked in bold numbers (6–18). The routing table of this

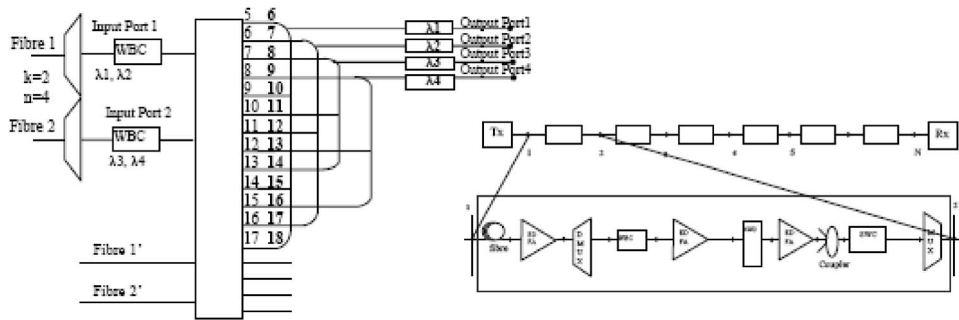


Fig. 5. (a) 2×2 WXC based on waveband routing. (b) Block diagram of the node is shown.

switch is outlined in Ref. [12]. For example, assume that the request is as follows: λ_1 requests to be routed to output port 2, λ_2 requests output port 4, λ_3 requests port 3, and λ_4 requests output port 1. To achieve this, λ_1 and λ_2 have to be converted to λ_{11} and λ_{12} while λ_3 and λ_4 have to be converted to λ_{14} and λ_{15} , respectively.

2. Summary of the Analytical Model

The analytical model that is presented in Ref. [25] is discussed here. All the components of the node are described by a model that deploys their transfer function. More specifically, the model of any component should take an input signal with the characteristics $P_{(o)}$, $ER_{(o)}$, $\sigma_{(o)}$, and $S_{(o)}$, which are, respectively, the average power of the input signal the extinction ratio, the overall relative intensity noise (RIN), and the amplified spontaneous emission (ASE) spectral density that affect the bit error rate (BER) and return a signal, with $P_{(1)}$, $ER_{(1)}$, $\sigma_{(1)}$, and $S_{(1)}$. After N concatenated devices, the model should present $P_{(N)}$, $ER_{(N)}$, $\sigma_{(N)}$, and $S_{(N)}$. These will be used for the calculation of the BER of the signal. For the WBC, the RIN analytical model describes the cross talk and gain modulation [26]. The cross-talk terms are accumulated through the node, and n cross-talk terms stemming from the AWG are added. The AWG, EDFA, SOA, and regenerator are all modeled as in Refs. [25,13]. The block diagram of the node is shown in Fig. 5(b). A fiber of length 100 km introduces losses (0.2 dB/km), and no other transmission effects are considered. For the EDFA that is required we assume unsaturated gain $G_o=1500$ and saturation power $P_{sat}=0.0063$ mW. The AWG other than loss (-8 dB/-12 dB/-15 dB) introduces interference and thus RIN of the order of 40 dB. The DMUX/MUX losses are of the order of -3 dB/6 dB/-10 dB depending on k . Moreover, the pump powers for the WBC are set at -6 dBm. The input signal has $ER=12$ dB, and $OSNR=58$. The coupler losses depend on $[M/n]$.

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