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Strictly Non-Blocking All-Optical-Cross-Connect Demonstrator for WDM Wavelength Path Networks

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Abstract. In this paper, we assess the design and performances of a strictly non-blocking all-optical cross-connect demonstrator node for WDM wavelength path networks. The all-optical cross-connect (AOXC) prototype was experimentally tested in a small 2×2 WDM network with a STM-16 bit stream per channel. The single and cascaded performance of the AOXC was also simulated and its results were validated with the experimental ones.

Keywords: wavelength division multiplexing, optical cross-connect, wavelength switching, optical switching

1 Introduction

The increase in traffic demand associated with surging applications is triggering a dramatic growth in capacity requirements of medium and long haul transport networks. Most network providers are aiming to dense wavelength division multiplexing (DWDM) to cope with the traffic capacity increase problem. The reasons for this choice are related to the capacity of these systems to offer an enormous potential of transmission throughput [1]. Therefore, this solution becomes one of the preferred techniques for further upgrading the capacity of the existing transmission links in a quick, efficient, and cost effective way, opening the door to new and potentially efficient all-optical routing schemes replacing what is nowadays performed by complex electronics [2,3].

To avoid an exponential growth in routing functions cost, it is essential to introduce a new all-optical layer that can handle high bit rate signals while providing simultaneously provision, restoration, and routing at the wavelength level, independently of the client electronic layer. All-optical WDM functionality could provide, in terms of performance and cost, an effective answer to the requirements of the transport network at the level of transmission path layers and may also pave the way to a simpler hierarchical network structure [4].

To achieve the goal of a multichannel and reconfigurable all-optical network, the employment

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of several enabling technologies is required, such as all-optical cross-connects (AOXC) and optical add-drop multiplexers (OADM). The provision of solutions to the practical issues of constructing large-scale networks that are robust to failure and traffic expansion is done smoothly in time and extent. In optical networks that are using DWDM technology, an all-optical cross-connect transparent to signal format is an essential part. The AOXC allows the optical network to be re-configurable on a wavelength-to-wavelength basis, allowing wavelengths to interchange and to optimize traffic patterns. In addition, it provides routing functions that simplify network growth and enhance network survivability.

The advances in optical technology are allowing the realization of wavelength routing elements such as a highly flexible AOXC [5]. Current AOXCs are still based on electronic switch fabrics that cross-connect the incoming data in the electrical domain. However, with the emergence of DWDM networks that carry a large number of wavelength channels, a new level of cross-connect in the optical domain is highly desirable [6].

Various AOXC architectures have been proposed. They are based on two elementary switching schemes: space switching and wavelength switching. For each of these switching schemes several architectures can be used [7,8]. It is not viable to determine one best solution for all cases because this depends on the respective specific application. However, it is possible to conclude that an AOXC based on space switching provides better transmission performance at the expense of complete modularity [7]. The development of strictly non-blocking AOXCs are necessary because the restoration or establishment of an optical path should have no effect on the previously established active optical paths [9].

In its most general architectural form, a strictly non-blocking space switching AOXC means that any combination of channels demands can be routed through the cross-connect and any additional demands that need to be routed will never require re-routing of the previously routed channels. Such an AOXC consists of five stages [6]: demultiplexing, wavelength conversion, space switching, multiplexing and amplification. Several AOXCs based on these stages have been proposed using non-blocking architectures for the space-switching matrix like: Crossbar, Benes, Spanke-Benes, and Spanke [8].

Advanced components such as an all-optical wavelength converter, realized as a space switch based on a clamped gain SOA (semiconductor optical amplifier) integrated with a demultiplexer, have been implemented in the laboratory. However, only a few components suitable for the practical and immediate implementation of transparent optical routing nodes are commercially available.

Our goal is to implement and test a cost effective, strictly non-blocking, all-optical cross-connect for wavelength path routing. This photonic node should be modular, should be transparent to bit rate and modulation format, and should be based on discrete, commercially available, optical components. This node has two main functions, routing of optical paths and optical path termination.

In this paper, we propose an enhanced version of an AOXC architecture using 1×2 optical switches that is based on the half Spanke switching structure, where the multiplexing stage of the AOXC is replaced by a power coupling stage. In this way, a completely non-blocking, re-configurable, and link modular AOXC was achieved. In Section 2, the AOXC architecture is described and its relevant characteristics are analyzed. In Section 3, laboratorial results are presented and are compared with simulation results in Section 4.

2 Proposed AOXC Architecture

The schematic diagram of the proposed AOXC is shown in Fig. 1. This prototype structure of the AOXC has two input ports, where each one handles two DWDM channels spaced by 200 GHz. The input signals can be routed to any of the two output ports. The AOXC has also a tributary port, which allows local add-drop functionality. For sake of simplicity, the 30 dB gain EDFAs placed at the output ports to compensate the AOXC attenuation, are not shown.

The multiwavelength signal from each incoming fiber is demultiplexed and passed by the tree space-switching structure to the selected optical power couplers of the output fiber. The configuration structure allows to direct the wavelengths to each output as function of the switch states. The switching scheme is the following:

$$\begin{bmatrix} Fout1 \\ Fout2 \\ Fdrop \end{bmatrix} = \begin{bmatrix} S1 \cdot S1' & S2 \cdot S2' & S3 \cdot S3' & S4 \cdot S4' & S5 \\ S1 \cdot (1 - S1') & S2 \cdot (1 - S2') & S3 \cdot (1 - S3') & S4 \cdot (1 - S4') & (1 - S5) \\ (1 - S1) & (1 - S2) & (1 - S3) & (1 - S4) & 0 \end{bmatrix} \cdot \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \end{bmatrix}.$$

In this notation, $S1$ to $S5$ and $S1'$ to $S4'$ are the switch states ''0'' or ''1'', λ_1 to λ_5 are the input wavelengths, and *Fout*1, *Fout*2 and *Fdrop* are the output ports as defined in Fig. 1. A ''0'' state means that the optical signal entering on the optical switch left port will be routed to the right bottom port, while a ''1'' state means that the optical signal will be routed to the right top port.

The used demultiplexers are designed to be compliant with the ITU 200 GHz frequency grid, having a 3 dB bandwidth of 135 GHz and a channel isolation higher than 46 dB. The 1 × 2 electro-mechanical optical switches used have an isolation higher than 50 dB. The insertion loss of these components is 1.0 dB.

By definition, this AOXC architecture is strictly non-blocking and transparent to bit-rate and data format due to its all-optical implementation. This AOXC is link modular but not wavelength modular. Since it is possible to add new input and output fibers without completely changing the AOXC, the addition of more DWDM channels at the existent fibers may require a drastic change on the AOXC. Link modularity is based on the fact that each input fiber has its own demultiplexer and optical switch, so that adding another input and output fiber requires the introduction of one more demultiplexer, passive coupler, and optical switch. On the other hand, the node is not wavelength modular, since adding a new wavelength channel requires to replace the demultiplexers when their maximum size has been reached. Therefore, the considered AOXC is limited scalable because to maintain network scalability, the AOXC must be wavelength modular [7].

By using passive optical couplers at the output stage, constraints on the number of optical channels will be imposed due to optical attenuation. In this sense, the use of an active optical coupler must be required in a large-scale structure.

The reconfiguration time of our AOXC is given by the electrical characteristics of the mechanical-optical switch matrix. The reconfiguration time is less than 20 ms, which is sufficient for operations of network reconfiguration and restoration [10]. This reconfiguration time is comparable with the reconfiguration time of commercial available optical switches based on MEMs [11].

In all-optical networks, the wavelength channels are considered as a transport resource allocated to a given data stream. An end-to-end connection can

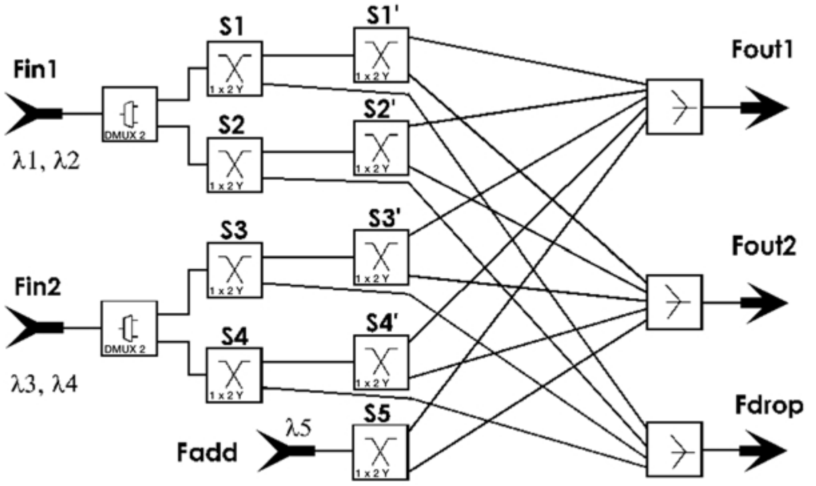

Fig. 1. Implemented AOXC structure. S_i and S_i' represent the switches.

either be supported by one wavelength (wavelength path—WP) or can physically be transported over different wavelengths through the transmission links (virtual wavelength path—VWP). In the latter case, the wavelength allocations are performed on a link-by-link basis and wavelength conversion must be, in principle, possible at all AOXC nodes [4]. The WP technique suffers from the limitation of the network extension, flexibility, scalability, and performance imposed by the total number of wavelengths available. To cope with this limitation, the same set of available wavelengths must be reused but only on fully disjointed parts of the network. The proposed AOXC architecture can provide the cross-connect for both WP and VWP networks. The introduction of a wavelength conversion stage will allow the use of this AOXC in a VWP network. The implemented AOXC was specified for a WP network, therefore no wavelength conversion is used and it is assumed that all wavelengths present at the AOXC inputs were different.

3 AOXC Test

This section describes the experimental results obtained by the AOXC implementation. The performance of the prototype was assessed by measurements of relevant characteristics such as: configuration capability, insertion loss, differential insertion losses, optical signal to noise ratio degradation, and bit error rate (BER) degradation of the channels.

Fig. 2 shows the results at output port 1 of the test configuration. In each input fiber, the signal from a broadband spectral source was inserted and the optical spectra at each output port was measured and shown for all possible configurations. With this result, it is

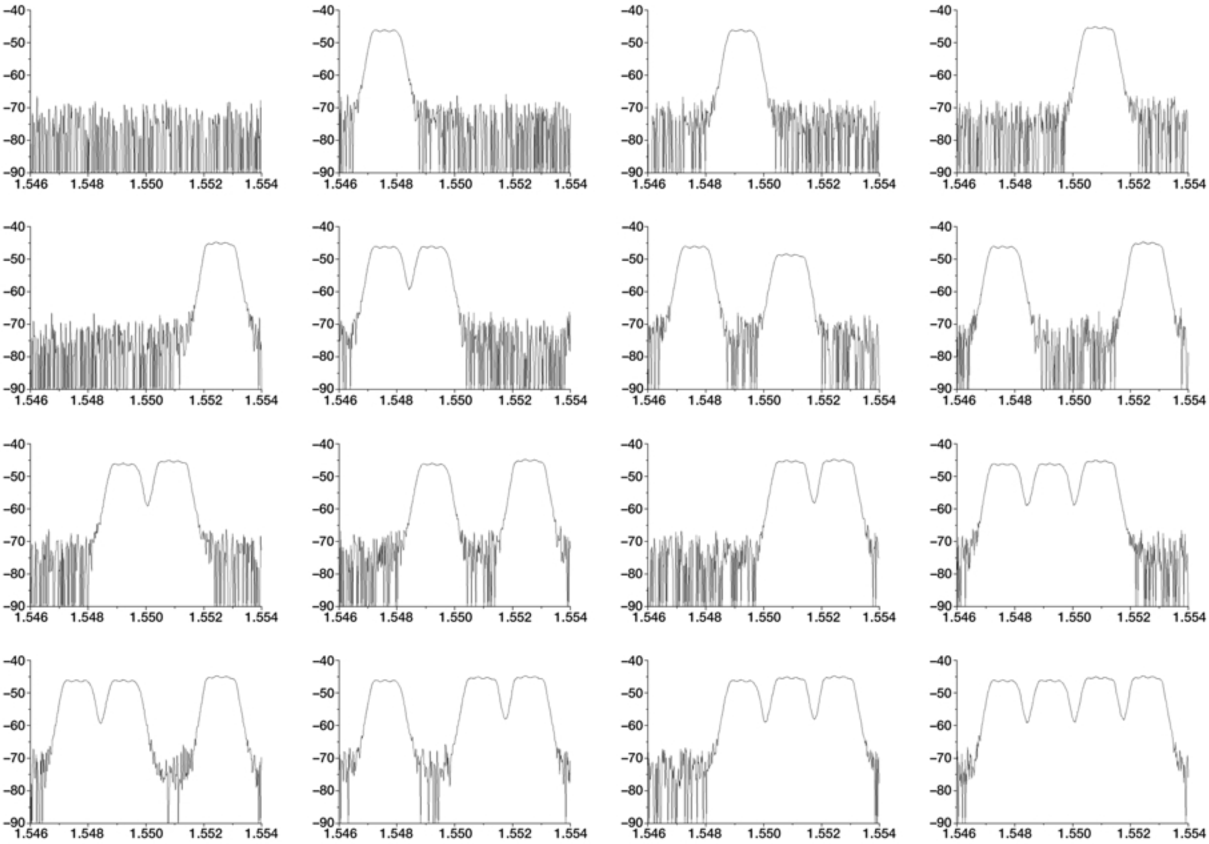

Fig. 2. Configuration possibilities. The power scale is arbitrary and the wavelength scale is between 1546 and 1554 nm.

Table 1. Switch states for each of the diagrams of Fig. 2 numbering from top to bottom and from left to right.

Diagram	$S1'$	$S2'$	$S3'$	$S4'$
1	0	0	0	0
2	0	0	0	1
3	0	0	1	0
4	0	1	0	0
5	1	0	0	0
6	0	0	1	1
7	0	1	0	1
8	1	0	0	1
9	0	1	1	0
10	1	0	1	0
11	1	1	0	0
12	0	1	1	1
13	1	0	1	1
14	1	1	0	1
15	1	1	1	0
16	1	1	1	1

possible to verify the complete AOXC configuration capability. Table 1 shows the state of the switches $S1'$ to $S4'$ for each of the 16 diagrams in Fig. 2. Since for this test we did not consider the use of the tributary port, the state for the switches $S1$ to $S5$ is 1.

Fig. 3 displays the optical spectra of one particular configuration where channel 3 is locally dropped, whereas channels 1 and 4 are routed to output 1 and channel 2 is routed to output 2.

The total number of optical components that a given DWDM signal passes through the AOXC determines the attenuation or insertion loss. Two important parameters exist here: the worst case of the insertion loss or the total insertion loss, and the differential insertion losses being the difference between the highest and the lowest loss path. A high worst-case insertion loss has a smaller impact than a high differential loss, since it can be compensated with an optical amplifier. A high differential insertion loss adversely affects the optical receiver and can reduce the signal to noise ratio (SNR) requiring a higher receiver dynamic range. In our prototype, the average insertion losses, measured before the output EDFAs, of all the input channels directed to the outputs 1 and 2 are 14.9 dB and 13.1 dB, respectively. These differences are due to the use of different types of passive optical couplers. The differential insertion losses are 1.0 dB and 1.2 dB for outputs 1 and 2, respectively. The insertion loss for the local tributary port is 4.5 dB. The output optical amplifier could easily compensate these high attenuation values.

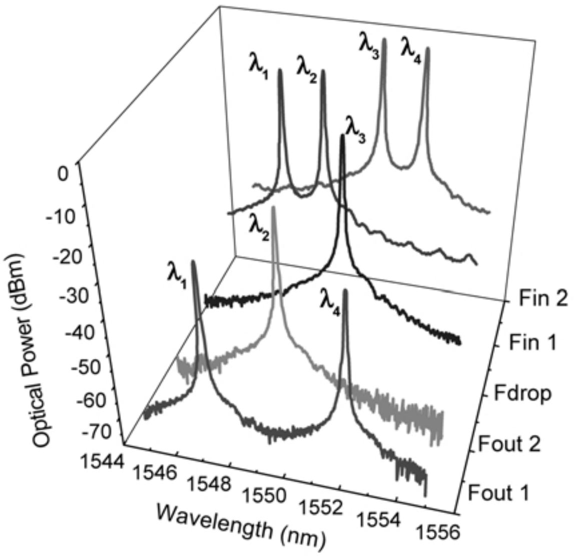

Fig. 3. Optical spectra for a specific switching configuration.

To investigate the operation, system performance, and feasibility of the proposed AOXC, two point-to-point links with 25 km + 12 km and 25 km + 20 km of standard single mode fiber (G.652) were connected by the AOXC routing node (Fig. 4). Each link transports two DWDM signals based at the ITU grid of 200 GHz spacing, with wavelengths of 1547.72 nm + 1549.32 nm and 1550.92 nm + 1552.52 nm, designated as channels 1, 2, 3 and 4, respectively. The signals from the four distributed feedback lasers (DFB), with a 50 MHz linewidth, were externally modulated through a Ti : LiNbO3 Mach-Zehnder intensity modulator at 2.48832 Gb/s (STM-16) with a non-return to zero (NRZ) 2^{15}–1 pseudo random bit sequence (PRBS) resulting in a 13 dB extinction ratio optical pulse stream. The AOXC local add channel could have any wavelength with the 200 GHz ITU frequency grid and was designated as channel 5.

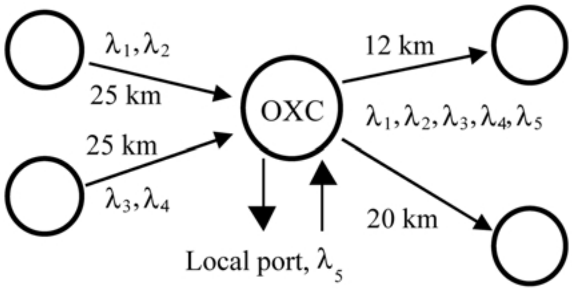

Fig. 4. Network structure.

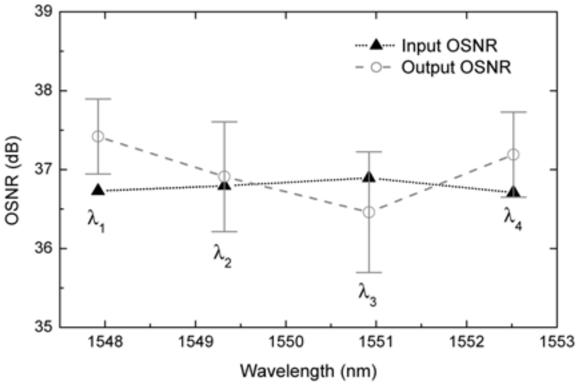

Fig. 5. OSNR degradation due to AOXC passing.

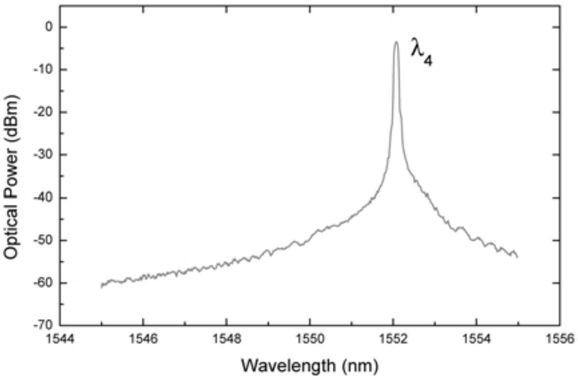

Fig. 6. Optical spectrum of channel 4 at the local drop port.

The optical signal-to-noise ratio (OSNR) could be used for DWDM channel quality monitoring [12], since it is simple to measure and has been suggested as adequate for BER specification [13,14].

The optical signal-to-noise ratio (OSNR) degradation due to crosstalk, arising from the demultiplexers and optical switches, was measured with a 12.5 GHz resolution of the OSA (optical spectrum analyzed). The input OSNR of the input channels 1 to 4 was 36.8, 36.8, 36.9, and 36.7 dB, respectively. Then, the OSNR of the four channels were measured at the AOXC outputs (before the EDFAs) for all the possible switching configurations. The outputs OSNR average values are 37.4, 36.9, 36.5, and 37.2 dB with standard deviations of 1.0, 1.4, 1.5, and 1.1 dB, for channels 1 to 4, respectively. These results are shown in Fig. 5, and indicate a small OSNR degradation due to the OXC routing, within the experimental uncertainty.

The first test was realized on a locally dropped channel. After propagation on 25 km of G.652 fiber. The channel 4 was dropped locally at the AOXC and the performance of the connection was assessed by the BER measurements on this channel against the receiver power. Fig. 6 shows the optical spectrum at the local drop port, when channel 4 is removed and Fig. 7 displays the respective BER. In order to compare the BER performance of the same channel at the AOXC input, the back-to-back receiver performance is also presented (0 km). The measurement floor (experimental measurement limit) and the 10^{-9} BER are indicated. The power penalty measured at a 10^{-9} BER is less than 0.1 dB for the dropped channel at the AOXC.

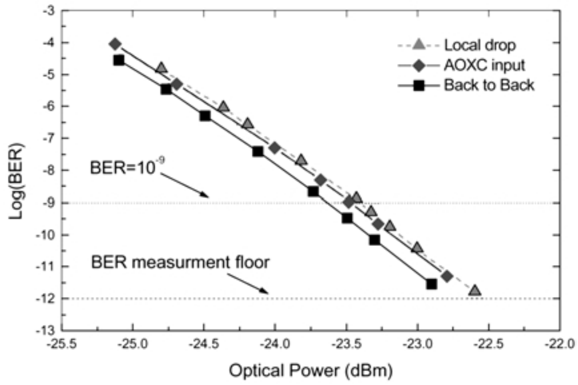

Fig. 7. BER performance for channel 4 that is locally dropped.

Channel 2 was tested after being routed at the AOXC. In the presence of channels 1 and 2 coming from input 1, they were routed to output 1 and propagated over 20 km of fiber. The optical spectrum of channels 1 and 2 at the receiver input after propagation over 45 km of fiber is shown in Fig. 8.

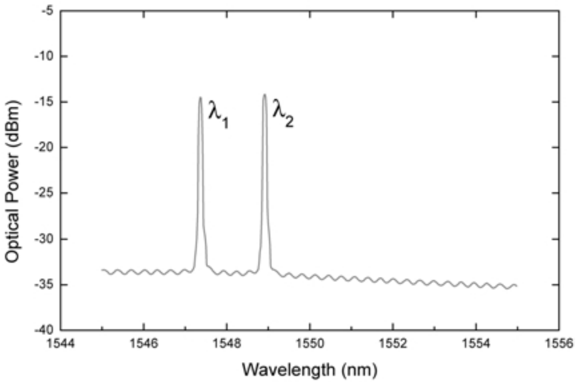

Fig. 8. Optical spectrum at the receiver.

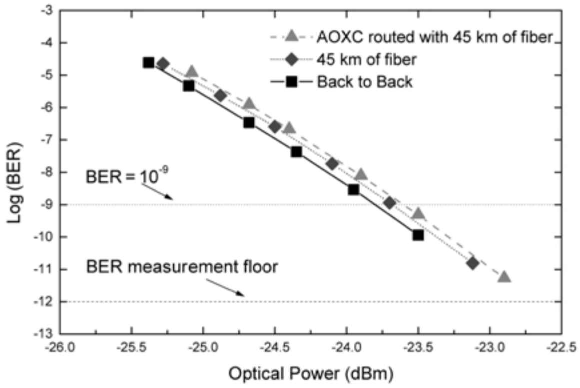

Fig. 9. BER performance for the channel 2.

Fig. 9 presents channel 2 BER performance, against the receiver power for the back-to-back operation (0 km), for the mid-span routed channel on the AOXC, and for the same channel after propagation on 45 km of fiber without being routed on the AOXC. The measurement floor (experimental measurement floor) and the 10^{-9} BER are again indicated.

The power penalty measured at a 10^{-9} BER is bellow 0.1 dB for the switched channel compared with the same channel after propagation on an equivalent fiber distance, which indicates a very low performance degradation due to AOXC switching, within the experimental uncertainty. Fig. 10 shows the detected eye diagram of channel 2 for a 10^{-9} BER. In this case, direct-detection with a very large receiver electrical filter was used.

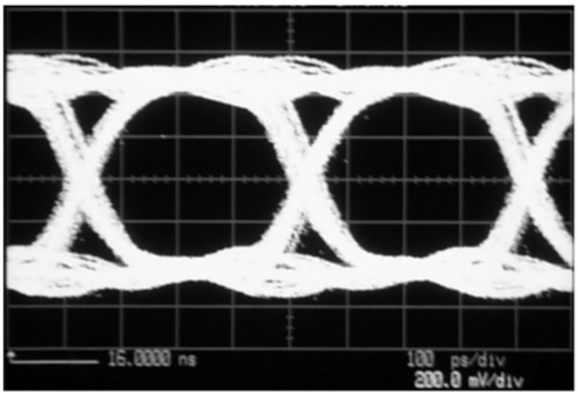

Fig. 10. Eye diagram for the channel 2.

4 AOXC Simulation

The experimentally implemented network was simulated in a commercial photonic transmission simulation tool, VPI Transmission Maker© [15]. In order to estimate the BER, a gaussian assumption for the noise and a total of 1024 data bits was used.

To perform the simulation, the functional parameters of the implemented components were used. The employed EDFA has a noise figure of 4.5 dB and the optical receiver sensitivity is − 20 dBm for a 10^{-12} BER.

The objectives of the simulation were to compare the experimental network performance measurements with the simulation results and to verify the cascadability of the AOXC by cascading a total of 30 nodes separated by 50 km each. To assure that the network performance degradation was only originated by the crosstalk and by the ASE (amplified spontaneous emission) noise of the EDFA, the fiber segments between the cascaded AOXCs were replaced by passive attenuators with an equivalent loss to a 50 km span of fiber (10 dB). Therefore, the chromatic dispersion and the non-linear effects of the optical fiber were ignored, although these two effects, if not properly compensated, will place a maximum limit on practical implementation [8].

The BER versus receiver optical power from channel 2 after the referred cascade of AOXCs is shown in Fig. 11.

For this channel, the power penalty at 10^{-12} BER was 1.4 dB for the 30-node cascade. This penalty is due to crosstalk, since ASE noise accumulation is

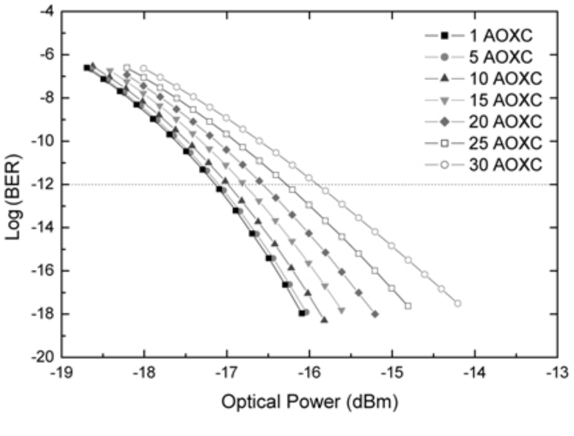

Fig. 11. BER performance of channel 2 after being cascaded by several AOXCs.

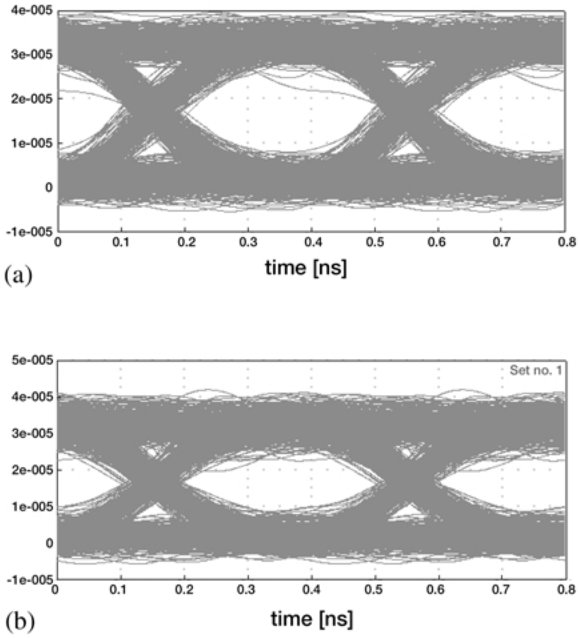

Fig. 12. Eye diagram of the detected channel 2. (a) After 1 AOXC, (b) after 30 AOXCs.

small, when compared with other architectures such as the ones reported in Wilfong et al. [6]. These advantages originate from the high isolation and low crosstalk of the used components (multiplexers, demultiplexers, and optical switches) and the low noise figure of the EDFAs.

Figs 12a and b show the detected eye diagram for channel 2 after being cascaded through 1 and 30 nodes, respectively. Figs 13a and b present a detected pulse sequence for channel 3 after 1 and 30 nodes, respectively.

These results show insignificant receiver sensitivity degradation due to switching in the AOXC, indicating that the signal quality is practically independent of the number of nodes.

5 Conclusions

This work describes the design, implementation, performance, and simulation of a cost effective strictly non-blocking AOXC architecture based on the half Spanke switching matrix and passive optical couplers, for wavelength path networks. An experimental prototype was implemented in a demonstration network and the system performance was verified, showing that an all-optical layer could be implemented and that the proposed AOXC is feasible, using commercial available optical components at a low implementation cost.

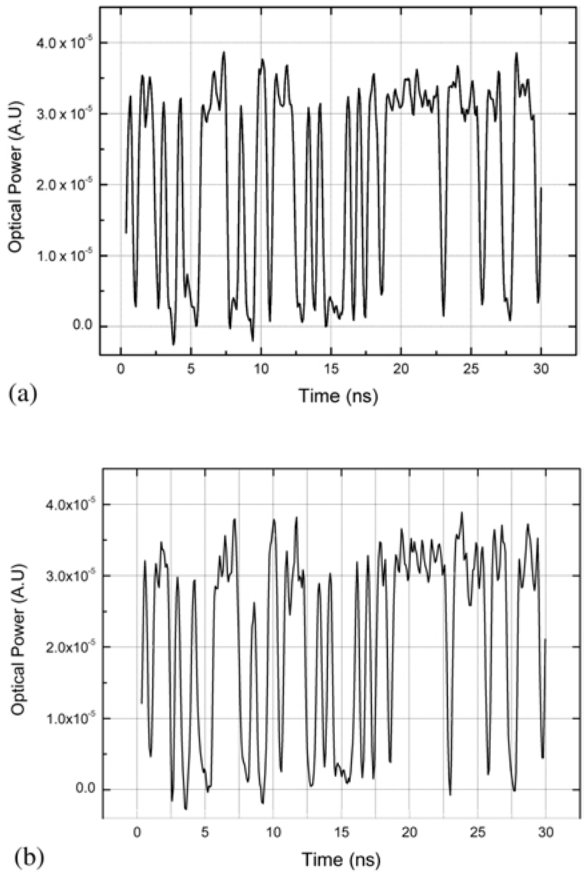

Fig. 13. Sequence of the detected channel 2. (a) After 1 AOXC, (b) after 30 AOXCs.

The experimental network was simulated and the cascadability of the AOXC was verified. The results show a very good degree of feasibility, cascadability, and compatibility with significant transmission distances and a high number of nodes of the proposed AOXC architecture.

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During 1999 he worked also in the Eurescom project BOBAN (building and operation broadband access networks) and during 2000 and 2001 he worked in the Eurescom project Freehands (Fiber and Radio Enhanced Integration in Heterogeneous Access Networks for Delivery of Broadband Services).

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