Design and Test of an Experimental Optical Cross-Connect

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Abstract

We describe the architecture of an optical cross-connect (OXC) which is modular in structure and is able to be upgraded to a virtual wavelength path from a wavelength path by adding wavelength converters. The additional feature of the OXC is the all-optical nature. It can be implemented with commercial components including mechanical optical switches. As a result of the test on the experimental OXC, it has been shown that 2.5 Gb/s signal can be transmitted via the OXC through 100 km length of an ordinary single mode fiber with 3 dB penalty.

I. Introduction

Due to the increasing demand of telecommunication services, it becomes necessary to provide higher transport capacity. Moreover, the services demand evolves quickly so that operators need to respond rapidly.

A flexible transport network would be achieved by introducing an optical path layer interfacing the transmission media layer with the electrical path layer. High capacity data streams are routed through the optical path layer by means of optical cross-connects (OXCs).

Among multiplexing technologies, needed to realize high capacity data streams, wavelength division multiplexing (WDM) is a promising approach. WDM can employ conventional technologies associated with intensity-modulation, direct-detection systems.

Among optical path layer technologies wavelength path (WP)/virtual wavelength path (VWP) scheme is of interest. In the WP scheme, each optical path is established between two nodes by allocating one wavelength for it. In the VWP scheme, the wavelengths are allocated link-by-link and thus the wavelength of the optical path can be converted at each node. The VWP scheme requires wavelength conversion at each node, so the node structure is more complicated than with the WP scheme. On the other hand, the WP scheme requires in general more wavelengths than that with the VWP scheme.

In recent years research and development on the optical transport network based on the WDM technology has been accelerated. In such a network the OXC is the key network element which is used to reconfigure the optical network. The basic function of the OXC is to cross-connect wavelength channels between incoming and outgoing fiber lines. If OXC systems are to become commercially successful, the initial versions must allow minimum investment but still support later incremental investment as traffic demand increases. Two kinds of modularity allow this feature: link modularity and wavelength modularity.

A network is transparent to the transmission format if all network functions are independent of the signal modulation format and speed. Bit rate transparency resulted from network transparency is useful to assure smooth network updating as the traffic demand increases.

Another useful OXC characteristic is the add/drop flexibility. Besides modularity, transparency, and add/drop flexibility, the OXC cost must be as low as possible. Thus, a significant parameter for the OXC is the complexity. Finally, optical paths, crossing several OXCs, must provide satisfactory transmission performances.

Several different type of OXCs have already been proposed. Iannone and Sabella [1] compared their architectures. The architecture of an OXC presented by Watanabe et al. [2] is shown in Fig. 1. It offers high modularity in wavelengths and makes it easy to upgrade a WP network to a VWP network. However, it employs optical transceivers (optical receivers and optical senders) which are costly at high bit rates. In this paper, the design and the test result of an OXC are described which is based on one of those presented in [2]. We also show that optical transceivers

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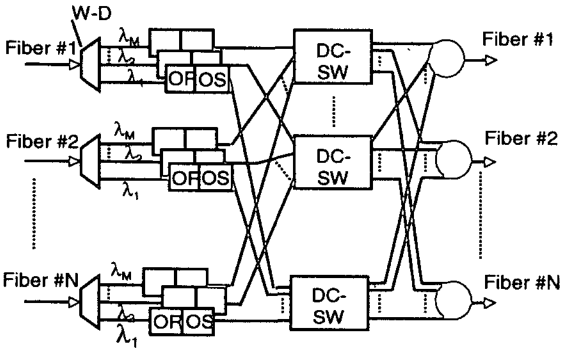
can be eliminated in the OXC without degrading the transmission performance.

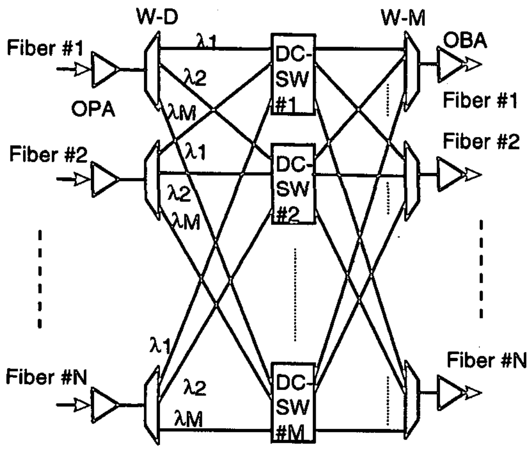


W-D: Wavelength demultiplexer
OR: Optical receiver
OS: Optical sender (WP: fixed wavelength, VWP: tunable wavelength)
○ : Combiner for WP/VWP (can be Wavelength multiplexer for WP)

Fig. 1. OXC architecture offering wavelength modularity (Ref. 2)

II. Architecture

The schematic diagram of the OXC architecture which will be described in this paper is shown in Fig. 2 [3]. It offers wavelength modularity.



W-D : wavelength demultiplexer
W-M: wavelength multiplexer
OPA : optical preamplifier
DC-SW: delivery-and-coupling-type optical switch
OBA: optical booster amplifier

Fig. 2. Optical cross-connect architecture

The OXC architecture can support an additional wavelength by adding one N x N delivery-and- coupling-type optical switch (DC-SW) where N is the number of incoming/outgoing fiber links of the OXC. The cross- connect has M optical paths on each fiber, i.e., the number of multiplexed wavelengths per fiber. The cross-connect consists of optical preamplifiers (OPAs), optical booster amplifiers(OBAs), wavelength demultiplexers (W-Ds), DC-SWs, and wavelength multiplexers (W-Ms). Optical receivers /optical transmitters (senders) which are located between wavelength demultiplexers and DC-SWs in Fig. 1 [2] have been deleted here because the loss in the OXC is not too high. Another reason that enables such simplification is the suppression of cross talk by using wavelength multiplexers which will be described later. This enables an all-optical processing in the OXC in addition to the simplicity in the structure. OPAs and OBAs are required for compensating the optical loss of the DC-SWs, W-Ds and W-Ms.

The incoming M WDM signals on each fiber are demultiplexed into individual wavelength signals by the W-D after being amplified by the OPA. The signals traverse the DC-SWs and W-Ms. Each signal is spatially switched in the DC-SW to its destination. W-Ms multiplex the switched signals to be launched into an outgoing fiber after being amplified by the OBA.

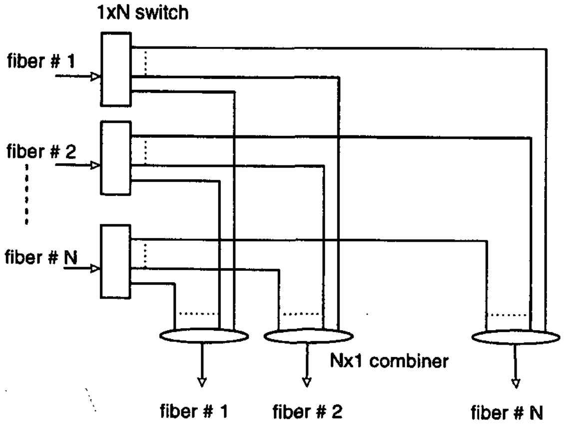


Fig. 3. Architecture for generic (N x N) delivery-and-coupling-type optical switch

By replacing the wavelength multiplexers with optical combiners and adding wavelength converters between wavelength demultiplexers and delivery-and-coupling-type optical switches this cross-connect can be upgraded from WP to VWP. The wavelength converter can be implemented with an optical receiver/optical transmitter using a tunable-wavelength laser diode. Jourdan et al. [4] have employed in their OXC all-optical wavelength converters using semi-conductor optical amplifiers. Note that local channels can be added or dropped at the input or the output of DC-switches. The generic (N x N) DC-SW architecture which is based on the one presented by [2] (Fig. 4) is shown in Fig. 3. The (N x N) DC-SW consists of N 1 x N switches and N N x 1 combiners. Note that the DC-SW can also be implemented using N^2 1 x 2 switches instead of 1 x N switches as shown in Fig. 4.

In this architecture, each signal of N channels can be delivered to any of the N x 1 combiners by the 1 x N switch. Obviously the case that multiple signals of the same wavelength are switched to the same destination is prevented. The delivered signals are coupled by the N x 1 combiners and outputted to W-Ms of the destination ports.

By using 1 x N switches which have uniform insertion loss for all output ports the insertion loss of the DC-SW becomes constant independent of the switching state. On the contrary, in the DC-SW consisting of 1 x 2 switches as shown in Fig. 4 [2] the insertion loss through the DC-SW varies depending on the switching state. It results in the level difference among output signals and the reduction of the signal-to-noise ratio for the signal having the lowest level.

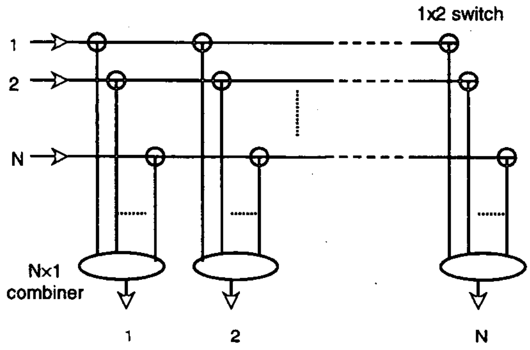


Fig. 4. Delivery-and-coupling-type optical switch using 1×2 switches (Ref. 2)

An OXC with a different structure can also be implemented using optical power splitters and tunable wavelength filters in addition to space switches and optical combiners as presented by Johansson [5]. However due to the broad bandwidth of tunable filters the channel spacing is wider than that using wavelength demultiplexers.

III. DESIGN OF THE OPTICAL CROSS-CONNECT

1. Design Concept

The design scale of the OXC introduced in this paper is summarized in Table 1. Both the number of links N and channel-wavelengths M are 4, respectively. Each signal is modulated at 2.5 Gb/s and follows ITU-T standardized STM-16. Thus this design can attain 40 Gb/s system throughput (2.5 Gb/s x 4 x 4) with full implementation.

Table 1. - Design scale of optical cross-connect

Items	Values	Note
Number of links (N)	4	
Number of wavelengths (M)	4	1554.1, 1555.7, 1557.4, 1559.0 nm
Transmission speed (Gb/s)	2.5	STM-16
System throughput	40 Gb/s	

Considering the chirped broadening spectrum of direct-modulation optical signals as well as the aging-induced wavelength shift, we adopted the channel spacing of 1.6 nm in accordance with the ITU-T grid. Thus we adopted four-multiwavelength signals ranging from 1554.1 to 1559.0 nm; the signal window falls in the flat-gain region of the erbium-doped fiber amplifiers.

2. Design Details

In the OXC shown in Fig. 2, cross talk is the main factor degrading the received optical power sensitivity, and is caused from finite ON/OFF ratios in DC-SWs and filtering properties in W-Ds as indicated by Koga et al. [6].

As can be seen in Fig. 2, when N signals traverse an N x N DC-SW the optical power of the N - 1 undesired components leaks into each of the switched signals if the switching ON/OFF ratio is finite. The leak components are the same wavelength as the signals, and they interfere with the signal as the beat-induced cross talk. According to [6], in order to hold the power penalty to less than 0.2 dB, the beat-induced cross talk should be lower than -28 dB. Since a total of 3 (= N - 1) undesired leak components become the cross talk in this cross-connect, each ON/OFF ratio in DC-SWs should be over 33 dB (= 28 + $10 \log_{10} 3$ dB). The amount of the beat-induced (intraband) cross talk after passing K OXCs shown in Fig. 2 can be expressed as K(N-1)/g. Here K is an integer, N and g are the number of links connected to the OXC and the ON/OFF (extinction) ratio of the 1 x N switch, respectively. The beat-induced cross talk is proportional to K since it occupies the same wavelength of the signal thus cannot be removed once coupled and accumulates through a cascaded network [7]. Note that when g is sufficiently high a large number of OXCs shown in Fig. 2 can be cascaded without excessive cross talk. Thus the OXC presented here is viable in a network consisting of interconnected OXCs.

In the implementation of the OXC shown in Fig. 2, the key parameter which influences the signal quality is the ON/OFF ratio of the optical switch. As the number of links (N) or that of the cascaded OXCs (K) becomes larger, the required ON/OFF ratio of the 1 x N switch should be higher. As an example, for N = 4 and K = 5 the ON/OFF ratio (g) of the switch should be higher than 40 dB. The value can be achieved by using commercial mechanical optical switches. Another problem occurring in the OXC shown in Fig. 2 as the result of the elimination of optical transceivers is the variation in the signal level among wavelength channels. The measured variation (defined here as the ratio of signal level with the highest power to that with the lowest power) among WDM channels at the output of the OBA was 2.0 dB. That of the input signal at the OPA was 0.4 dB. The variation among WDM channels causes the degradation in the signal-to-noise ratio which is influenced by the cross talk. When the OXCs are cascaded the problem will become more serious. To overcome the problem, variable optical attenuators can be inserted in the OXC to adjust the power level of each demultiplexed channel.

Compared to the OXC presented in Fig. 1 [2], the OXC shown in Fig. 2 is advantageous due to the simplicity in its structure as well as the transparency which have been resulted from the elimination of optical transceivers. However, the OXC presented here requires the higher ON/OFF ratio in optical switches for cascading of OXCs. It also needs compensation for the variation of levels among WDM channels.

In the W-D, the total cross talk power is nearly double the adjacent channel cross talk power. Since this cross talk consists of different wavelength components it is simply added to the signal power and behaves as waveform distortion. In this case, -20 dB level of cross talk causes no power penalty as reported in [6]. In Fig 2, as indicated by Zhou et al. [8] it can be seen that by using wavelength multiplexers instead of optical combiners the cross talk components generated by wavelength demultiplexers are suppressed. This can be explained as follows. Referring to Fig. 2, it can be seen that the output signals from DC-SW #2 consist of λ_1 and λ_3 which have been generated as cross talk components at wavelength demultiplexers. However, at wavelength multiplexers wavelength components different from λ_2 are filtered out. Thus cross talk of the same wavelength component having greater influence is reduced by using wavelength multiplexers instead of optical combiners. This is the main advantage of the OXC architecture presented here compared to the link modular type presented in [6] where optical combiners are used.

If the wavelength multiplexers in Fig. 2 are replaced by M x 1 optical combiners, the beat-induced cross talk can be expressed as $K(N-1)/g + 2(K-1)FCT$ [7], where FCT (filter cross talk) represents the cross talk due to the wavelength demultiplexer. This means that even when g is sufficiently large the cascading of OXCs ($K > 1$) gives the beat-induced cross talk due to filter cross talk. Since the amount of filter cross talk is usually higher than the target value for the beat-induced cross talk (-28 dB), it can be concluded that for cascading of the OXCs shown in Fig. 2 the wavelength multiplexers cannot be replaced by optical combiners.

3. Devices

Optical switch. The (4 x 4) DC-SW consists of 4 1 x 4 switches and 4 4 x 1 optical combiners, referring to Fig. 3. As the 4 x 1 combiners, commercial ones were used which have insertion loss of under 7 dB. As 1 x 4 switches commercial mechanical switches were used since they have very low cross talk (under 60 dB) and loss of under 1 dB. They have maximum switching speed of 15 ms.

In order to improve the switching speed the mechanical switches may be replaced by solid state optical switches which have a switching time of under 2 ms. However 1 x 4 switches of that type have maximum insertion loss of 4 dB and isolation of over 25 dB.

Wavelength-demultiplexer/wavelength multiplexer. W-Ds and W-Ms were realized by commercial arrayed-waveguide gratings (AWGs). The AWGs can multiplex or demultiplex up to 8 channel signals spaced at 1.6 nm with the cross talk of under -22 dB. The AWG is thermally controlled with a thermoelectric cooler. The insertion loss for each channel is under 7 dB with a full width at half maximum of 0.64 nm (40% of channel spacing). Polarization dependency is under 0.5 dB.

4. Power Budget

The power budget for the optical cross-connect is shown in Table 2. Referring to Fig. 2, it can be seen that the per channel input power of the optical preamplifiers is in the range from -20 to -15 dBm. The range has been chosen to keep the optical signal-to-noise ratio at a satisfactory level. With up to 1 dBm (per channel) output power of the optical booster amplifiers the gain of the optical cross-connect is 21 dB (with -20 dBm input at the optical preamplifier). Thus assuming 0.28 dB/km fiber loss the spacing between optical cross-connects can be as long as 70 km. The output of booster amplifiers has been limited to the level for the possibility of employing dispersion-shifted fiber as a transmission medium which induces the cross talk at high signal levels [6]. If the number of incoming/outgoing links of the OXC become larger (> 4), the loss in the DC-SW increases due to the higher loss of the optical combiners. Consequently, the output power of the DC-SW will decrease.

Table 2. - Power budget for the optical cross-connect

Per channel input power of optical preamplifier	-20 ~ -15 dBm
Per channel output power of optical preamplifier	3.5 ~ 6.5 dBm
Output power of wavelength demultiplexer	> -4 dBm
Output power of DC-SW	> -15 dBm
Per channel output power of optical booster amplifier	< 1 dBm

IV. Experiment

The prototype of the OXC has been implemented and we have constructed a test-bed in the laboratory. It consists of one cross-connect node and an additional node where the wavelength division multiplexed signal is generated as shown in Fig. 5. Note that one of the output channels from the DC-SW is dropped and connected to an optical receiver.

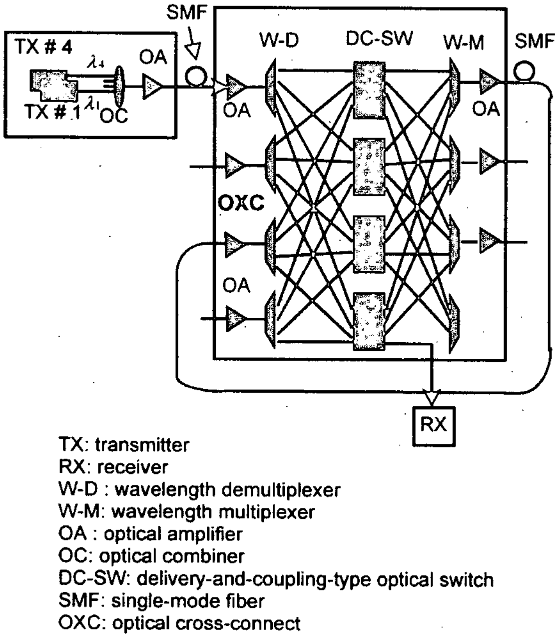


Fig. 5. Test-bed system configuration

The measured spectrum of the signal dropped at the DC-SW is shown in Fig. 6. The signal at 1554.1 nm has a level higher than the design target of -15 dBm. The measured cross talk (interband) is about -25 dB meeting the target value of -20 dB.

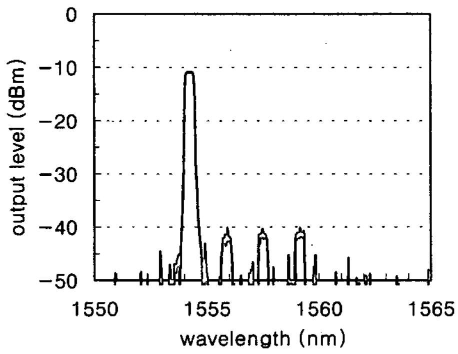


Fig. 6. Spectrum of the signal dropped at the DC-SW

The bit error rate (BER) versus received optical level of the dropped signal (2.5 Gb/s, 1554.1 nm) after transmission through the ordinary single mode fiber is shown in Fig. 7. For the fiber lengths of 40 and 60 km, only the fiber span between the WDM transmitter and the OXC is required. However, for 100 km length an additional span connecting the output of the OXC and its input has been used. The power penalty at 10^{-10} BER for 100 km length is about 3 dB compared to the 0 km (back to back) case. The power penalty has been caused mainly by the dispersion in the fiber. The measured amount of the additional power penalty in passing through the OXC was 0.4 dB for the 40 km length of a fiber. This has been measured by using a 0 km fiber (optical attenuator) between the output and the input of the OXC while a 40 km fiber has been used between the transmitter and the OXC.

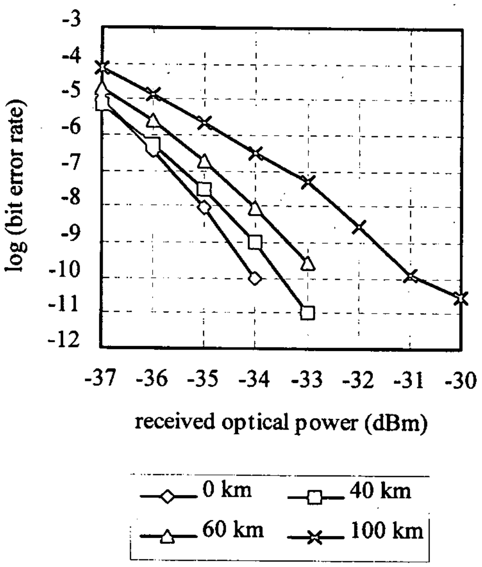


Fig. 7. Bit error rate versus received optical level of the dropped signal (2.5 Gb/s, 1554.1 nm) after transmission through the ordinary single mode fiber

V. Conclusion

In this paper, the design of an optical cross-connect has been described which is modular in wavelength and is able to be upgraded from a wavelength path to a virtual wavelength path. The cross-connect interfacing 4 links and 4 wavelength channels in each link can be implemented with commercially available components such as arrayed-waveguide gratings, mechanical optical switches and optical combiners. Its additional feature is the all-optical processing requiring no optical-electrical conversion. A prototype of the cross-connect has been implemented and a test-bed has been constructed. As a result of the measurement on the transmission performance, it has been confirmed that 2.5 Gb/s signal can be transported via the OXC through 100 km length of ordinary single mode fibers with 3 dB penalty.

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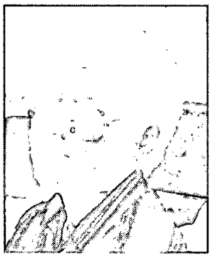

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