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*Published in:*

I E E E Photonics Technology Letters

*Link to article, DOI:*

[10.1109/68.920763](https://doi.org/10.1109/68.920763)

*Publication date:*

2001

*Document Version*

Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

*Citation (APA):*

Liu, F., Zheng, X., Pedersen, R. J. S., & Jeppesen, P. (2001). New types of 2x2 wavelength-switching blocks for optical cross-connects. *I E E E Photonics Technology Letters*, 13(5). <https://doi.org/10.1109/68.920763>

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# New Types of $2 \times 2$ Wavelength-Switching Blocks for Optical Cross-Connects

Fenghai Liu, Xueyan Zheng, Rune J. S. Pedersen, and Palle Jeppesen

**Abstract**—Two types of modular  $2 \times 2$  wavelength-switching blocks are proposed in this letter. A  $2 \times 2$  fixed wavelength-switching block can cross-connect two fixed channels between two fibers, and a  $2 \times 2$  tunable wavelength-switching block can cross-connect any two channels between two fibers. These modular blocks can be used to build scalable multiwavelength cross-connects in optical networks.

**Index Terms**—Optical add/drop multiplexer, optical cross-connect, optical networks, optical space switch, wavelength conversion.

## I. INTRODUCTION

**W**AVELENGTH-DIVISION MULTIPLEXING (WDM) not only increases fiber transmission capacity but also simplifies network operation by introducing the optical path layer concept [1]. Multiwavelength cross-connects are key elements in reconfigurable WDM networks.

The conventional way of making an optical cross-connect needs to demultiplex and multiplex all WDM channels in the fibers [2]. This is efficient in some central nodes where most traffic needs to be cross-connected. In many cases where the node only needs to cross-connect a few channels between fibers, the conventional way is less efficient since more and more WDM channels are packed into the fibers. Demultiplexing and multiplexing all channels also impose filtering effect on bypassing WDM channels that will limit the cascadability of optical cross-connects. A  $2 \times 2$  multiwavelength cross-connect (MWXC) based on modular wavelength-switching blocks was previously proposed [3] and realized [4], which supports cross-connection of part of the WDM channels between two fibers.

The structure consists of a number of wavelength-switching blocks in series, and each block cross-connects two channels with **the same** wavelength between two fibers. In many cases, the channels to be cross-connected between two fibers will not necessarily have the same wavelength. As illustrated in Fig. 1, two optical ring networks are connected via an optical cross-connect node. The channel from Ring #1 that needs to be cross-connected to Ring #2 has wavelength  $\lambda_i$ , while the channel from Ring #2 that needs to be cross-connected to Ring #1 has wavelength  $\lambda_j$ . Wavelength translation is necessary when  $\lambda_i \neq \lambda_j$  in order to avoid wavelength blocking.

In extension of our previous work, wavelength converters are added into the wavelength-switching blocks. Thus, two new

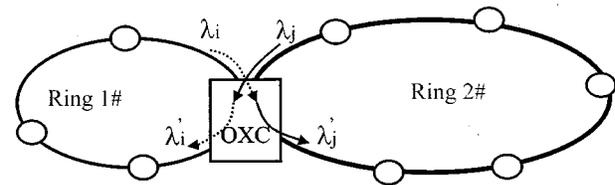


Fig. 1. Optical cross-connect node connecting two ring networks where channels with different wavelengths need to be interchanged.

types of wavelength-switching blocks are proposed in this letter, i.e., a  $2 \times 2$  fixed wavelength-switching block that can cross-connect two fixed wavelength channels between two fibers, and a  $2 \times 2$  tunable wavelength-switching block which can cross-connect any two channels between the two fibers due to the use of tunable optical add/drop multiplexers (OADMs) and tunable wavelength converters.

## II. CONSTRUCTION OF A $2 \times 2$ FIXED WAVELENGTH SWITCHING BLOCK

The structure of a  $2 \times 2$  fixed wavelength-switching block is shown in Fig. 2(a). Two OADMs are connected to the input fibers with wavelengths corresponding to the channels to be cross-connected, e.g., OADM #1 connected to fiber #1 has the center wavelength  $\lambda_1$  and OADM #2 connected to fiber #2 has the center wavelength  $\lambda_2$ . The two dropped channels are fed into a  $2 \times 2$  optical space switch. Two wavelength converters are attached to the add ports of the OADMs respectively, and each wavelength converter has the fixed output wavelength same as the add/drop wavelength of the associated OADM. When the space switch is in “cross” state, the dropped channel from fiber #1 will be added to fiber #2 after the wavelength has been changed from  $\lambda_1$  to  $\lambda_2$  by the wavelength converter. Since the original channel with  $\lambda_2$  in fiber #2 has been dropped by OADM #2, no blocking will occur. In the same way, the dropped channel from fiber #2 will be added to fiber #1 after the wavelength has been changed from  $\lambda_2$  to  $\lambda_1$  by another wavelength converter. All other channels in the two fibers just pass through the block.

When the space switch is in “bar” state, the dropped channel from fiber #1 will be connected back to fiber #1 after being converted into the same wavelength, and the dropped channel from fiber #2 will be connected back to fiber #2 in the same way. There will be no channels interchanged between the two fibers in this case.

The  $2 \times 2$  wavelength-switching block used in [3] and [4] can be considered as a simplified version of this type, where

Manuscript received September 25, 2000; revised February 5, 2001.

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Publisher Item Identifier S 1041-1135(01)03743-0.

OADM's in the block had the same drop wavelength and no wavelength converter was needed.

### III. CONSTRUCTION OF $2 \times 2$ TUNABLE WAVELENGTH-SWITCHING BLOCK

Fig. 2(b) shows the structure of a  $2 \times 2$  tunable wavelength-switching block which is similar to the  $2 \times 2$  fixed wavelength-switching block except that tunable OADM's and tunable wavelength converters are used instead of fixed wavelength ones. Any two channels to be cross-connected between two fibers are first dropped by the two tunable OADM's tuned to the wavelengths of the corresponding channels. The two dropped channels are switched in the optical space switch operated in "cross" state, and then each proceeds to its tunable wavelength converter. Each wavelength converter always tunes its output wavelength to the same as the add/drop wavelength of the OADM which is connected to, and converts any input to this wavelength. The converted channels are added to the respective output fibers through the add ports of the OADM's. When the space switch is set to "bar" state, no channels will be interchanged.

Tunable OADM's can be realized in different ways, e.g., acous-optic filters [5] or tunable Bragg gratings [6]. Many types of wavelength converters reported can be made tunable by using tunable optical probe sources [7], [8]. The  $2 \times 2$  space switches are commercially available, e.g., mechanical optical switches or thermo-optic switches.

### IV. $2 \times 2$ MULTIWAVELENGTH CROSS-CONNECTS

A  $2 \times 2$  multiwavelength cross-connect can be built by cascading these  $2 \times 2$  wavelength-switching blocks, as shown in Fig. 3. The cross-connectivity in such an MWXC depends on the type of the  $2 \times 2$  wavelength-switching block and the number of blocks. When each fiber hosts  $M$  wavelength channels, a fully reconfigurable MWXC needs a cascade of  $M^2$  of  $2 \times 2$  fixed wavelength-switching blocks, or a cascade of  $M$  of  $2 \times 2$  tunable wavelength-switching blocks. In the case that full reconfiguration is not necessary in one OXC node, less blocks are needed. The node can always be upgraded smoothly by adding more blocks when the need for cross-connection increases. It can be found that the  $2 \times 2$  fixed wavelength-switching block possesses a simple structure, but is only suitable for optical cross-connect nodes with low degree of connectivity, while the  $2 \times 2$  tunable wavelength-switching block is a little more complex, but it is more flexible and suitable for OXC nodes with high degree of connectivity.

### V. EXPERIMENT

In order to demonstrate the basic concept of the proposed  $2 \times 2$  wavelength-switching blocks, a  $2 \times 2$  fixed wavelength-switching block is experimentally constructed, as shown in Fig. 4. In the construction, two fiber Bragg grating based Mach-Zehnder interferometric OADM's with fixed add/drop wavelength are used. Two tunable wavelength converters based on cross-gain modulation in semiconductor optical amplifiers (SOAs) are connected to the OADM's. The optical space switch is simply replaced by manual connections since the crosstalk

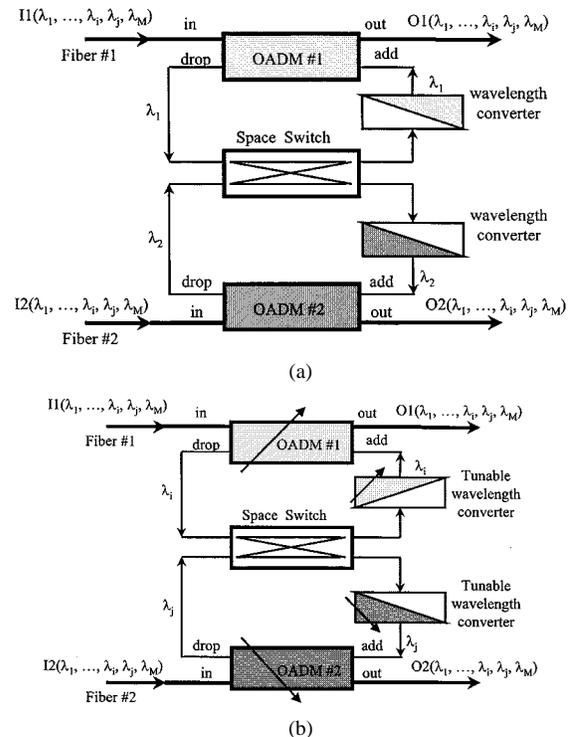


Fig. 2. Schematic diagram of  $2 \times 2$  wavelength-switching blocks. (a) Fixed wavelength type. (b) Tunable wavelength type.

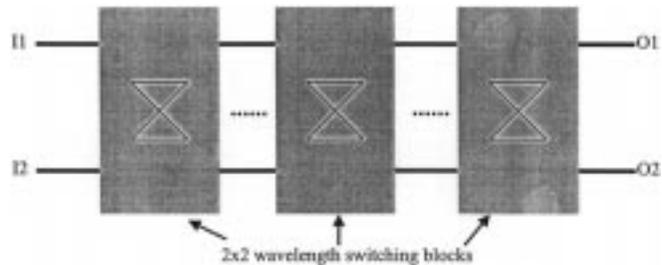


Fig. 3. A  $2 \times 2$  multiwavelength cross-connect constructed by using  $2 \times 2$  wavelength-switching blocks.

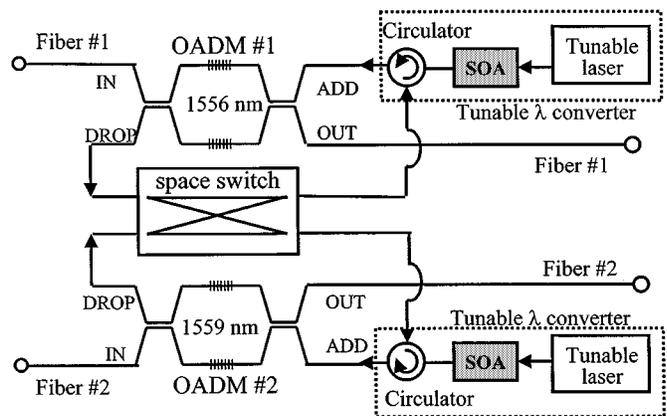


Fig. 4. Experimental setup of a  $2 \times 2$  fixed wavelength-switching block.

from a mechanical optical switch is very low [4] and switching speed is not the issue studied here.

Eight WDM channels separated by 200 GHz are hosted in each input fiber, and each channel is modulated by a NRZ signal

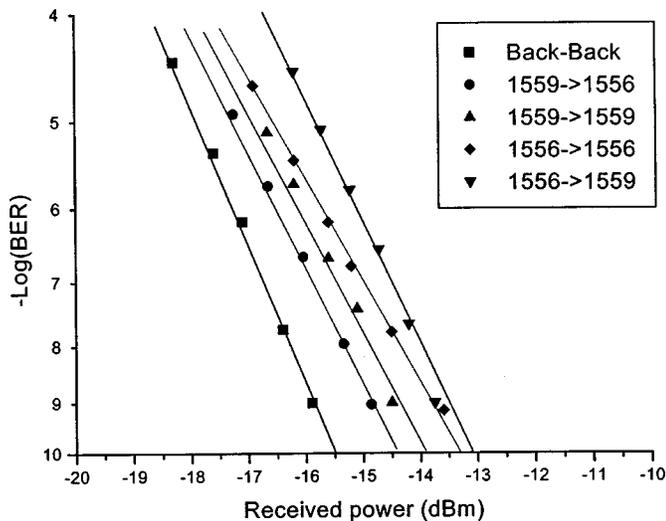


Fig. 5. Bit-error-rate curves after the wavelength-switching block.

at 10 Gb/s with a PRBS pattern length of  $2^{31} - 1$ . Fiber #1 is connected to OADM #1 with center wavelength 1556 nm and fiber #2 is connected to OADM #2 with center wavelength 1559 nm. The output wavelength of wavelength converter associated with OADM #1 is set to 1556 nm, while the output of the wavelength converter associated with OADM #2 is set to 1559 nm. The connections from the two drop ports of the OADMs to the input ports of the wavelength converters are manually changed according to a space switch in “cross” or “bar” state. After the wavelength-switching block, the 1556-nm channel from fiber #1 and the 1559 nm channel from fiber #2 are demultiplexed and detected by a PIN receiver. With reference to Fig. 5, bit-error-rate (BER) curves have been measured for the following four situations.

- 1) Channel at 1556 nm dropped from fiber #1 is converted to 1559 nm and added to fiber #2, referred to as 1556  $\rightarrow$  1559.
- 2) Channel at 1559 nm dropped from fiber #2 is converted to 1556 nm and added to fiber #1, referred to as 1559  $\rightarrow$  1556.
- 3) Channel at 1556 nm dropped from fiber #1 is converted to the same wavelength and added back to fiber #1, referred to as 1556  $\rightarrow$  1556.
- 4) Channel at 1559 nm dropped from fiber #2 is converted in the same wavelength and added back to fiber #2, referred as 1559  $\rightarrow$  1559.

Among these four situations, the first and second are corresponding to the optical switch in “cross” state, while the third and fourth are corresponding to the optical switch in “bar” state. For comparison, a base-line BER curve is also measured for the receiver, which is referred to as Back-Back in Fig. 5. From Fig. 5 we can see that the power penalty for the four cases varies from 1 to 2.3 dB, which mainly stems from the wavelength converters used in the block. Wavelength conversion from long to short wavelength (1559  $\rightarrow$  1556)

exhibits the smallest penalty while wavelength conversion from short to long wavelength (1556  $\rightarrow$  1559) shows the highest penalty. That happens because the gain peak of the SOA shifts to longer wavelength for higher input power, which leads to a poor signal extinction ratio for conversion from short to long wavelength [8]. The wavelength conversion scheme used in the present experiment is very simple and we should emphasize that wavelength conversion does not always introduce power penalty. On the contrary, a wavelength converter can also provide power equalization between the cross-connected channels and the bypassing channels and some wavelength conversion schemes can even provide a regenerative function [9], [10].

By replacing the fixed wavelength OADMs in Fig. 4 with tunable ones, a  $2 \times 2$  tunable wavelength-switching block can also be constructed, since the wavelength converters used in the setup are tunable.

## VI. CONCLUSION

Two kinds of  $2 \times 2$  wavelength-switching blocks have been proposed in this letter, namely, a  $2 \times 2$  fixed wavelength-switching block and a  $2 \times 2$  tunable wavelength-switching block. These blocks can be used to build scalable multiwavelength cross-connects to the full reconfiguration. A  $2 \times 2$  fixed wavelength-switching block has been experimentally demonstrated, and it can be upgraded to a  $2 \times 2$  tunable wavelength-switching block if tunable OADMs are used.

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