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Dynamically selective multiwavelength cross-connect based on fibre Bragg gratings and mechanical optical switches

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A dynamically selective multiwavelength cross-connect for wavelength division multiplexed (WDM) networks based on fibre Bragg gratings (FBGs) and optical switches is reported. Dynamically single- or multi-channel cross-connect functionality can be realized according to control of the optical switches and the FBGs' arrangement. Bit-error-rate performance with negligible power penalty is achieved in a 2.5 Gb $s^{-1} \times 3$ WDM channels over 100 km conventional single-mode fibre (SMF) network demonstration. The characteristics of low channel crosstalk, uniform channel loss, high scalability and cascadability, and low cost of this device could provide more reconfiguration flexibility and network survivability for WDM networks.

1. Introduction

The multiwavelength cross-connect switch (M-XC) will play a key role in future optical multiwavelength wavelength-division-multiplexing (WDM) networks [1–4]. The importance of the M-XCs, and the closely related WDM add-drop multiplexer (ADM), is that they allow the optical network to be reconfigured on a wavelength-by-wavelength basis to optimize traffic, congestion, network growth, and survivability. Conventional optical wavelength-fixed M-XCs usually consist of N sets of $1 \times N$ demultiplexers (DMUXs) and $N \times 1$ multiplexers (MUXs) in a back-to-back configuration to allow interchange of wavelengths between input and output fibres in a prearranged pattern. But wavelength-fixed M-XCs do not have any automated rearrangabililty, thus restrict their network reconfiguration flexibility. On the other hand, the wavelength-selective (i.e. rearrangable) M-XCs can be implemented by adding space division switches in the configuration [2, 4] to select wavelengths and rearrange them in the spatial domain. However, besides the MUXs and DMUXs, extra components for space division switches such as waveguide directional couplers [5, 6], semiconductor optical amplifiers [3, 7], low-gain erbium-doped fibre amplifiers [8], an acousto-optic tunable filter (AOTF) [9], and arrayed-waveguide grating multiplexes [10, 11] are required. The drawbacks of complicated designs, controls, and increased insertion losses of these space-division switch elements have to be conquered for various applications.

Recently, dynamic wavelength-selective ADMs comprising reflective fibre Bragg gratings (FBGs) and optical switches (OSWs) were proposed [12, 13]. System experiments also demonstrated its add/drop/pass-through functionalities [14]. In this paper, we present a dynamically wavelength-selective 2×2 M-XC, extending the previous concept, using optical-circulator (OC) and mechanical-OSW pairs combined with single or multiple FBGs with appropriate connecting paths. Dynamic single- or multi-channel cross-connect can be realized according to the control of the OSWs and the FBG arrangements. The cross-connection of International-Telecommunication-Union (ITU) WDM channels with low insertion loss and high cross-connect contrast characteristics can be obtained. Bit-error-rate (BER) performance with negligible power penalty has also been confirmed in a network demonstration of 2.5 Gb $s^{-1} \times 3$ WDM channels over 100 km of conventional single-mode fibre (SMF).

2. Operation principle

Figure 1a shows the conventional WDM MUX/DMUX cross-connect configuration with a space-division switch inserted between the MUX/DMUX pairs. Figure 1b shows the proposed wavelength-selective M-XC. It consists of two three-port OCs, two $1 \times N$ me-

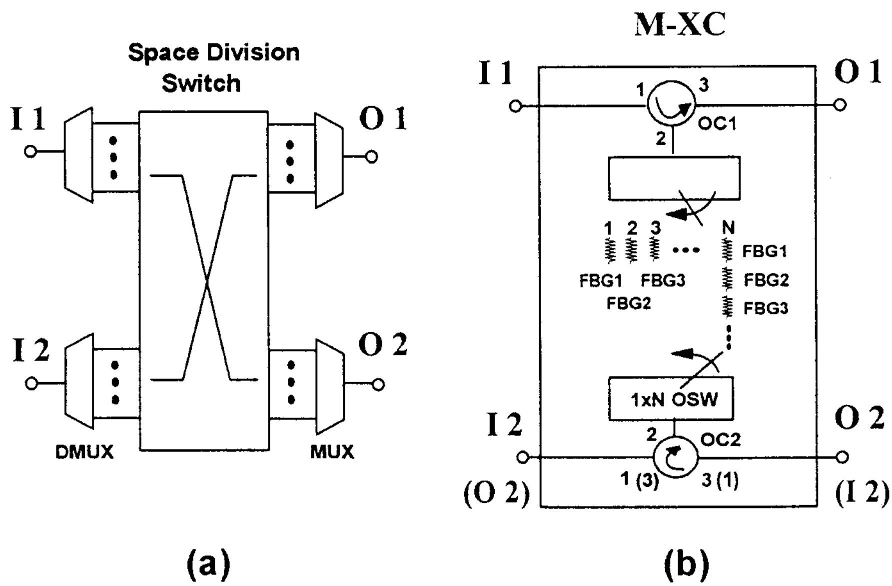


Figure 1 Schematic diagrams of (a) the conventional WDM MUX/DMUX cross-connect with a space division switch, and (b) the proposed dynamically selective multiwavelength cross-connect switch. OC: optical circulator. FBG: fibre Bragg grating. OSW: mechanical optical switch.

chanical OSWs, and N pieces of the photo-imprinting FBG chains. Each central reflective wavelength of the FBG_i is designed to match the WDM-channel-signal λ_i. For practical operations, the central reflective wavelength of FBG should meet the ITU WDM standardization, and its passband width should be large enough to cover the corresponding channel signal with high reflectivity. By switching the switch-pair to the proper position, the desired channel signals can be spatially cross-connected (here, passed through the FBG chain) to another fibre link. In the meantime, other channel signals will be reflected by the FBG chain, then leave through port 3 of the OC1, and continuing their forward propagation (here, termed as passed-through) in the same fibre link. When two or more FBG cascading chains are properly arranged between the switch-pair, multiple channel cross-connection can be realized. Simple $1 \times N$ mechanical OSWs can be used for this function with a switching time of about 0.3 ms. There are two input ports I1 and I2, as well as two output ports O1 and O2 in the M-XC. These two input ports can operate in the same direction or opposite direction (i.e. bi-directionally) simply by re-arranging the three ports (number 1, 2 and 3) of OC2 clockwise or counter-clockwise as shown in Fig. 1b, dependent on the network structures in which the M-XC is located.

To investigate the feasibility of this M-XC, two sets of multiwavelength transmitters were externally modulated at 2.5 Gb s^{-1} through a $LiNbO_3$ intensity modulator as shown in Fig. 2. Each transmitter set comprised three DFB lasers based on the ITU proposal of 200

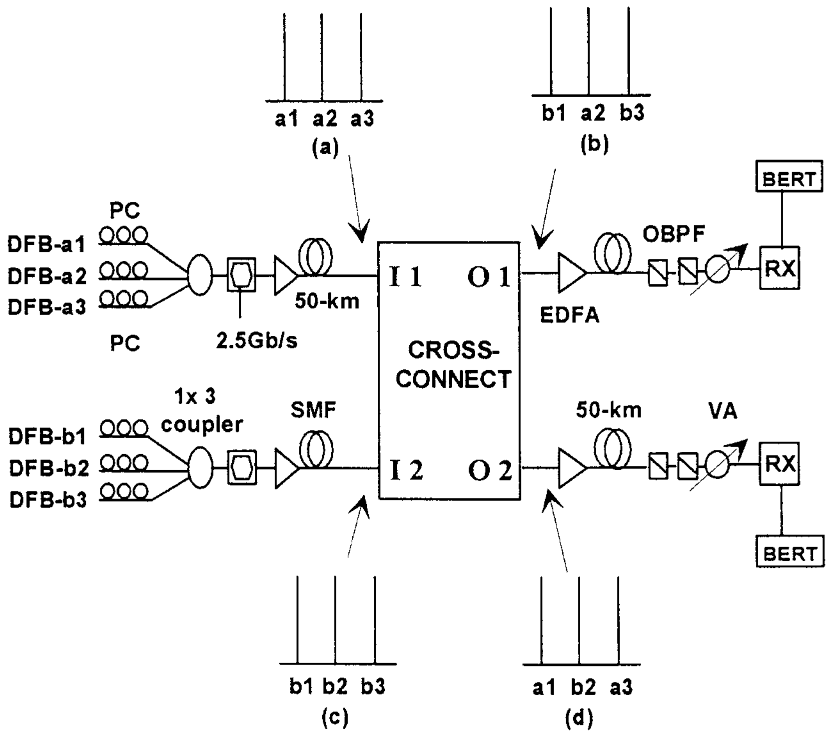


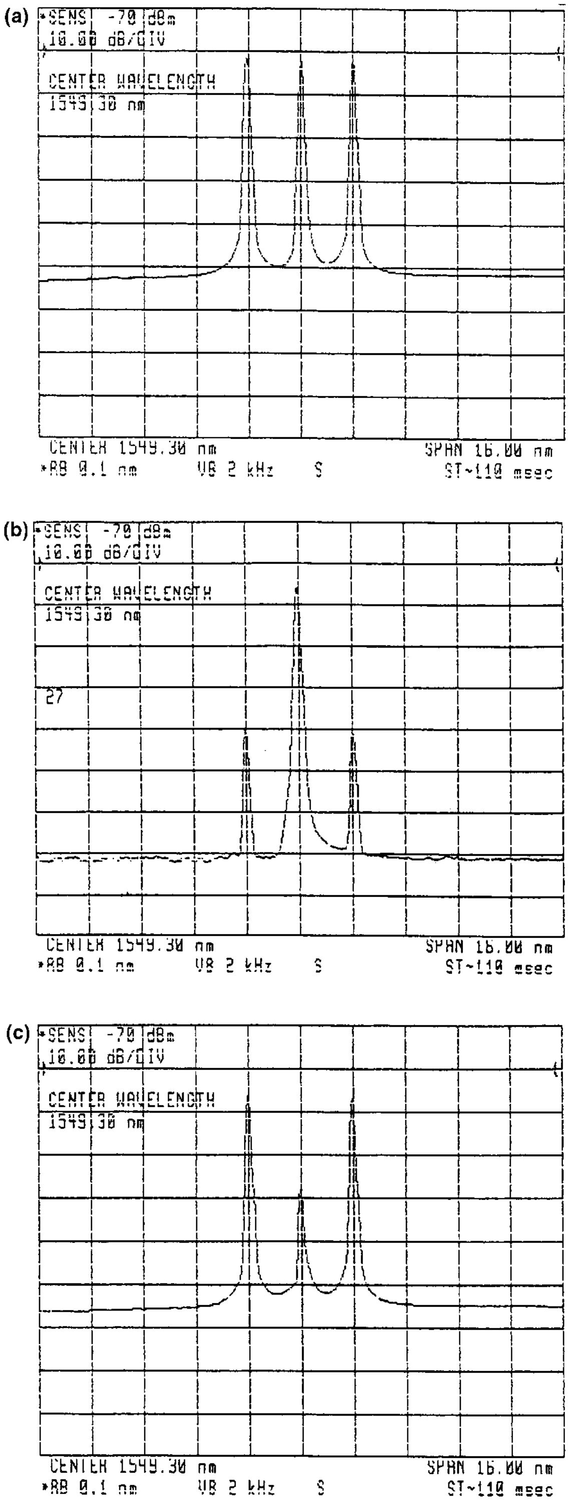
Figure 2 Experimental setup. EDFA: erbium-doped fibre amplifier. VA: variable optical attenuator. SMF: single-mode fibre. PC: polarization controller. RX: optical receiver. OBPF: optical band-pass filter.

GHz (1.6 nm) spacing with the same wavelength sets of 1547.7, 1549.3, and 1550.9 nm, respectively, being used. The polarization controllers (PCs) were employed to adjust the polarization state of each DFB laser for matching the maximum power operation with the 2.5 Gbs^{-1} $LiNbO_3$ intensity modulator. The total 100 km transmission link of SMF is arranged. Two erbium-doped fibre amplifiers (EDFAs), each having a saturated output power of +13.5 dBm and a noise figure of < 5 dB, are employed to provide the required power to compensate for the link loss. Two optical narrow bandpass filters (OBPFs) with 3 dB bandwidth of 1.3 nm and an insertion loss of 1.6 dB were used at the receiving end to select the desired WDM channel for detection. A PINFET receiver with a sensitivity of −32.5 dBm at a BER of 1×10^{-9} was used for the BER performance testing. The averaged cross-connect (reflective- or passed-through path) insertion losses of this M-XC are all about 3.7 dB. These result from the insertion losses of all components in the corresponding propagating paths of OSWs, OCs, and FBGs. The insertion loss of each OC from port 1/2 to port 2/3 is about 1.2 dB and the insertion loss of each OSW is about 0.5 dB. The isolation of each OC is about > 48 dB. The 3 dB passband width and reflectivity of the FBGs are 0.25 nm and 99%, respectively. All connectors used are physical contact connectors with return loss of < −45 dB.

3. Results and discussions

The dynamically selective cross-connecting operations can be easily realized by switching the OSW pairs to the appropriate FBG-chain according to the reconfiguration plan. The 'a' set of signals (DFB-a1, -a2, and -a3) were firstly launched into the M-XC via port I1 and the switches connected them to the FBG with a reflective central wavelength of 1549.3 nm. Figure 3a–c shows (a) the input three-WDM-channel signals at port I1, (b) the passed-through signal of 1549.3 nm at port O1, and (c) the cross-connected signals at port O2. Note that a high optical signal-to-noise ratio of about 62 dB and 45 dB for the passed-through and cross-connected channels is achieved (Fig. 3b–c). The former is due to the filtering-out of the most amplified spontaneous emission from the EDFA by the narrow, sharp passband of FBG. Two small spectral components contaminating the reflected signal in Fig. 3b are due to the back reflection of OC1 and all the connectors. On the other hand, one small spectral component at 1549.3 nm contaminating the cross-connected signals in Fig. 3c results from the 1% transmittivity of the FBGs. The maximum crosstalk level is −33 dB and −22 dB for the passed through and cross-connected channels, respectively. However, these crosstalk levels seem not to degrade the system performance. When another 'b' set of three-channel signals (DFB-b1, -b2, and -b3) were launched via port I2 with the same wavelengths as those in the 'a' set, as mentioned above, the complete cross-connect function is realized. Similar signal spectra to those in Fig. 3a have been observed from the output ports of O1 and O2 with power levels about 3.7 dB down. Figure 4 shows the BER performance for the 'a' set transmitters against the received channel power for the back-to-back (0 km), pass-through (100 km) at 1549.3 nm, and cross-connect (100 km) at 1550.9 nm cases. Note that a negligible power penalty of only

Figure 3 Signal spectra of the M-XC when launched with one set of signals at input port I1 and with the switch pairs connected to the FBG with a central reflective wavelength of 1549.3 nm; (a) the input three-WDM-channel signals at port I1, (b) the passed-through signal of 1549.3 nm at port O1, and (c) the cross-connected signals at port O2.


(a)
*SENS -70 dBm
10.00 dB/DIV
CENTER WAVELENGTH
1549.30 nm
CENTER 1549.30 nm
SPAN 16.00 nm
*RB 0.1 nm
VB 2 kHz
S
ST~110 msec
(b)
*SENS -70 dBm
10.00 dB/DIV
CENTER WAVELENGTH
1549.30 nm
27
CENTER 1549.30 nm
SPAN 16.00 nm
*RB 0.1 nm
VB 2 kHz
S
ST~110 msec
(c)
*SENS -70 dBm
10.00 dB/DIV
CENTER WAVELENGTH
1549.30 nm
CENTER 1549.30 nm
SPAN 16.00 nm
*RB 0.1 nm
VB 2 kHz
S
ST~110 msec

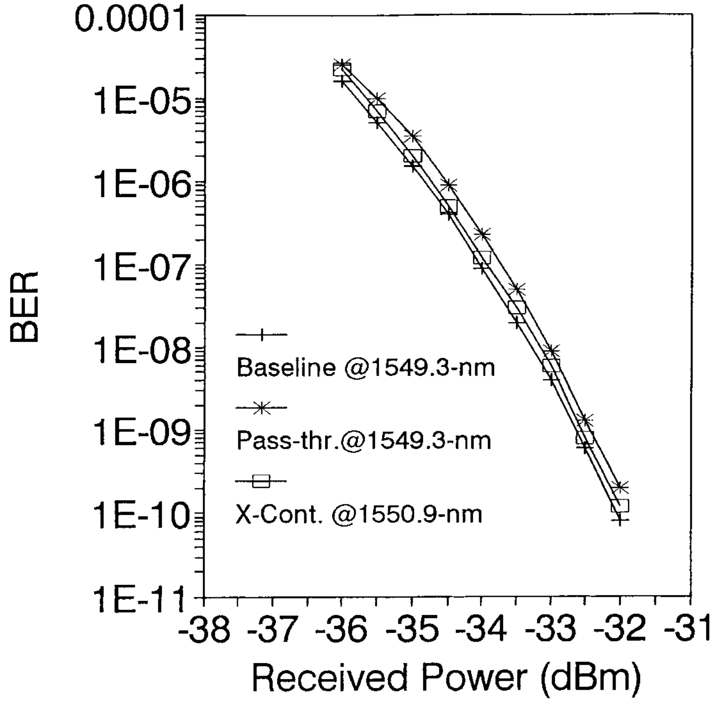


Figure 4 The BER performance against the received channel power for the back-to-back (0 km), pass-through (100 km) at 1549.3 nm, and cross-connect (100 km) at 1550.9 nm, respectively.

0.3 dB was observed in this 2.5 Gb $s^{-1} \times 3$ WDM channel network. In consequence, the system operation and performance confirm the feasibility of the proposed M-XC.

There are several important features for this device in this experiment with potentially low crosstalk, uniformly low channel insertion loss, high scalability and cascadability, and low cost. First, the low channel crosstalk (i.e. high cross-connect contrast ratio) can be improved up to >50 dB by employing ultra-high-reflectivity ($\approx$100%) FBGs, low back reflection (>60 dB) components and angled physical contact (APC) connections. Second, the low insertion loss characteristics of 3.7 dB for this device is uniform for all cross-connected and passed-through channels, and is almost independent of the device size due to the near spectral-loss independent characteristics of the OSWs and OCs in the 1.55 μm band. Third, the characteristics of low device loss with least channel loss-imbalance for both of these FBG-and-optical-switch-based ADMs [14] and M-XCs will not restrict the cascading node numbers of ADMs and M-XCs in the all-optical WDM networks. Furthermore, the simple structure and operating mechanism of this device could make it easily expandable to a larger size, with minor modifications, e.g. inserting a new FBG chain between the OSWs for the desired cross-connection. Thus, high scalability and cascadability of this device are obtained. Finally, because of the successful development of FBGs [15] and other components of mechanical switches and circulators, this device has potentially a lower cost than that of other space-division-switch-based or wavelength-converter-based M-XCs.

4. Conclusions

In summary, we have demonstrated a dynamically selective 2×2 multiwavelength cross-connect switch based on fibre Bragg gratings and optical switches. Dynamically single- or multi-channel selectivity can be easily realized by connecting the appropriate fibre Bragg gratings. Negligible power penalty has been achieved in a 2.5 Gb $s^{-1} \times 3$ WDM channel over an experimental 100 km system. The selective cross-connect function with features of low channel crosstalk, uniformly low channel loss, high cascadability and scalability, and low cost may allow this device to provide more reconfiguration flexibility and survivability in WDM networks.

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