Optical and Quantum Electronics **31** *(1999) 77–83*

Reconfigurable WDM add/drop multiplexer based on optical switches and fibre Bragg gratings

SHIEN-KUEI LIAW
Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsin-Chu 300, Taiwan

KEANG-PO HO
Department of Information Engineering, The Chinese University of Hong-Kong, Shatin, NT, Hong-Kong, China

YUAN-KUANG CHEN
Institute of Electro-Optical Engineering, National Sun Yat-Sen University, Kaohsiung 700, Taiwan

CHIEN-CHUNG LEE
Outside-plant Division, Chung-Hwa Telecommunication Laboratories, Yang-Mei 326, Taiwan

Received 25 February 1998; accepted 10 June 1998

A reconfigurable wavelength-division-multiplexing (WDM) add/drop multiplexer (WADM) is constructed using optical switches (OSWS) and fibre Bragg gratings (FBGs). Selected one or two channel(s) can be added/dropped at the same multiplexer by properly controlling the optical switch pair and fibre Bragg grating arrangement. A four-channel system is experimentally demonstrated for a data rate of 2.5 Gb s^{-1} and a single-mode fibre (SMF) distance of 100 km. A negligible maximum power penalty of only 0.3 dB is observed when compared with back-to-back transmission.

1. Introduction

Wavelength-division-multiplexing (WDM) add-drop multiplexer (WADM) is one of the essential components for optical networks with dense WDM transmission, especially in a reconfigurable ring topology [1, 2]. Conventional optical ADMs usually consist of a $1 \times N$ WDM demultiplexer (DEMUX) followed by an $N \times 1$ WDM multiplexer (MUX). The first DEMUX is used to separate the multi-wavelength input signals into N wavelength ports. One or several desired channel(s) are dropped from the fibre link. The second MUX is used to combine the remaining channels and the added channel(s) into the output of the WADM. The interference-based MUX/DEMUX using multi-layer dielectric-coating technique and array waveguide grating (AWG) are the commonly used MUX/DEMUX technologies having narrow to moderate WDM channel-spacing from 0.8 to several nanometres, and channel insertion loss from 3 to 8 dB. Several channels can be added/dropped simultaneously in those WADMs. However, those WADMs operating at fixed frequencies determined by the WADM MUX/DMUX and both WDM MUX and DEMUX are expensive components. In another low-cost alternative, a reflective fibre Bragg grating (FBG) combining with two optical circulators (OCs), one in front of and the other at the rear end of the FBG, was demonstrated for its single-frequency add/drop capacity [3].

A wavelength-tunable WADM, able to access all wavelengths of the WDM-based optical network, provides the flexibility to satisfy the reconfiguration requirement and to enhance network survivability. The tuning functionality can be achieved by combining FBGs with two optical switches (OSWs). Indeed, wavelength-tunable WADMs based on similar arrangement have been reported using silica-based AWG routers [4, 5] and acoustic–optic tunable filters (AOTF) [6]. In another study [7], a dynamic wavelength selective WADM node constructed by OSWs and FBGs was proposed to select one wavelength at a time. However, system assessments of the add/drop/pass functionality have not yet been addressed in most of these papers. Here, we propose a simple low-cost WADM to realize either single- or two-channel add/drop function by properly controlling the OSW pair and FBGs. The wavelength can be the same as in the International Telecommunication Union (ITU) draft standard WDM-channel grid. System demonstration of one-channel add/drop/pass-through is also carried out here using an OSW pair combining with two 3-port OCs as proposed in [8]. The add/drop of the WDM channel with low insertion loss and high add/drop contrast characteristics can be obtained. A negligible power penalty of 0.3 dB is observed for a four-channel ITU-wavelength-based system with a data rate of 25 Gbs^{-1} per channel using 100 km of single-mode fibre (SMF).

2. Proposed WDM add/drop configurations

Figure 1a, b shows the schematic diagrams of the proposed wavelength-tunable WADM for single- and two-channel add/drop, respectively. In Fig. 1a, the WADM consists of two 3-port OCs, two $1 \times N$ mechanical OSWs, and N pieces of the photo-imprinting FBG chains. The central reflect wavelength λ_i ($1 \leqq i \leqq N$) of the FBG_i is designed to match the WDM-channel signal λ_i. In practical operations, each central wavelength of the FBG should meet the ITU-WDM standard, and its passband width should be large enough to cover the corresponding channel signal with high reflectivity. The desired WDM signal can be dropped by switching the optical switch pair to proper port. For instance, when the switch pair is connected to port 2 of the OC pair, the launched channel signal λ_2 is reflected by FBG_2 and then dropped from port 3 of OC1. Meanwhile, the other WDM-channel signals are passed through the WADM via port 3 of OC2 on the right-hand side. Moreover, a new signal λ_2' with the same wavelength of λ_2 can be added to the FBG-based WADM through port 1 of OC2.

With similar function, when a two-FBG chain is properly arranged between the OSW pair as shown in Fig.1b, two channels can be added/dropped from the same WADM; tunable ability can also be realized. Two 4-port OCs are used to replace the two 3-port OCs for two-channel add/drop function. Two more $1 \times N$ mechanical OSWs are connected to port 3 of OC1 and port 2 of OC2, respectively. The channel selectivity can be achieved easily by connecting the OSWs to the proper position to select the desired channels. For instance, the upper OSW pair is connected to the FBG chain consisting FBG_2 and FBG_j, while the lower two OSWs are connected to FBG_2 and FBG_j, respectively. The lanched channel signal λ_i is reflected by one FBG_j and then dropped from port 3 of OC1. Also, the

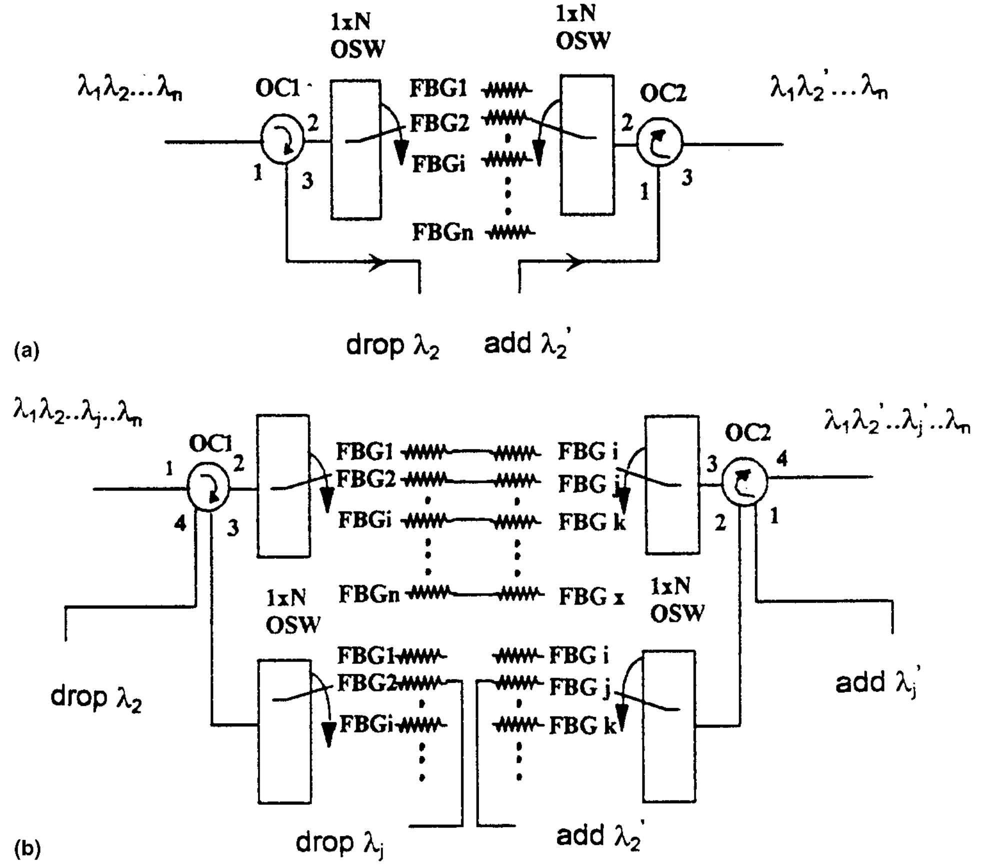


Figure 1 Schematic diagrams of the proposed dynamically (a) single and (b) dual-wavelength add/drop multiplexer using two 3-port and two 4-port optical circulators, respectively.

channel signal λ_2 drops from port 4 of OC1 after it is reflected twice by the upper FBG chain ($FBG_2 + FBG_i$) and the lower FBG chain (FBG_2). The other WDM-channel signals pass through the WADM device via port 4 of OC2 on the right-hand side. Meanwhile, two channel signals of λ_2' and λ_i' of the same wavelength λ_2 and λ_i can be added to the WADM device via ports 2 and 1 of OC2, respectively. The add channel λ_i' comes from port 1 of OC2 and is reflected twice by the lower FBG chain (FBG_j) and the upper FBG chain (FBG_i + FBG_2) before it passes through port 4 of OC2, and continues its forward propagation. For the purpose of two-channel add/drop at the same time, the total possible combination numbers of the FBG chains (two different FBGs per chain) are $N = n\,(n-1)$. Simple $1 \times N$ mechanical OSW pair can be used for this function when the channel selection could be done slowly (0.5–1 ms). Fast channel switching (μs speed) will require opto-electrical switches.

3. Experimental demonstration of one-channel add–drop

Figure 2 shows the experimental configuration to verify system performance of the one-channel add/drop WADM. Four distributed feedback (DFB) lasers based on the

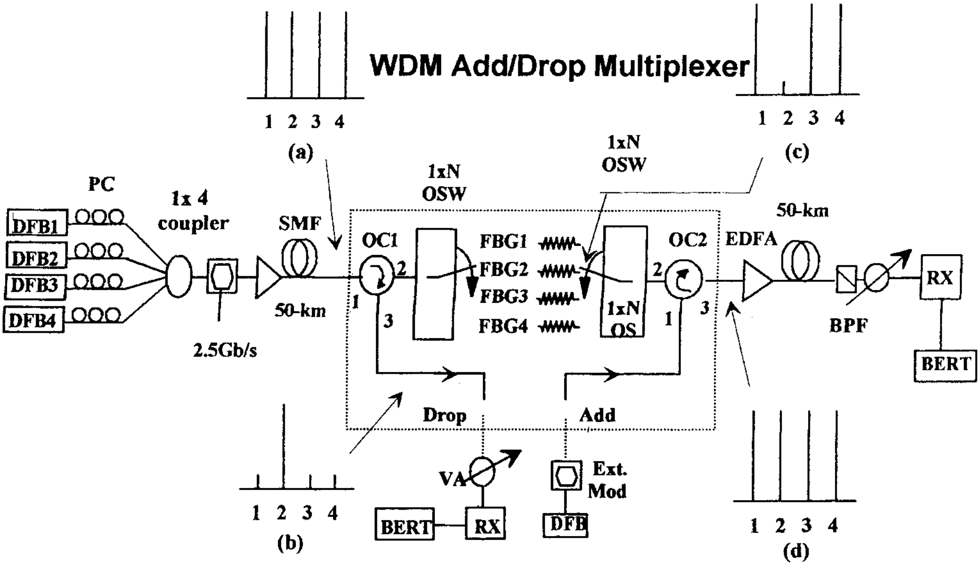
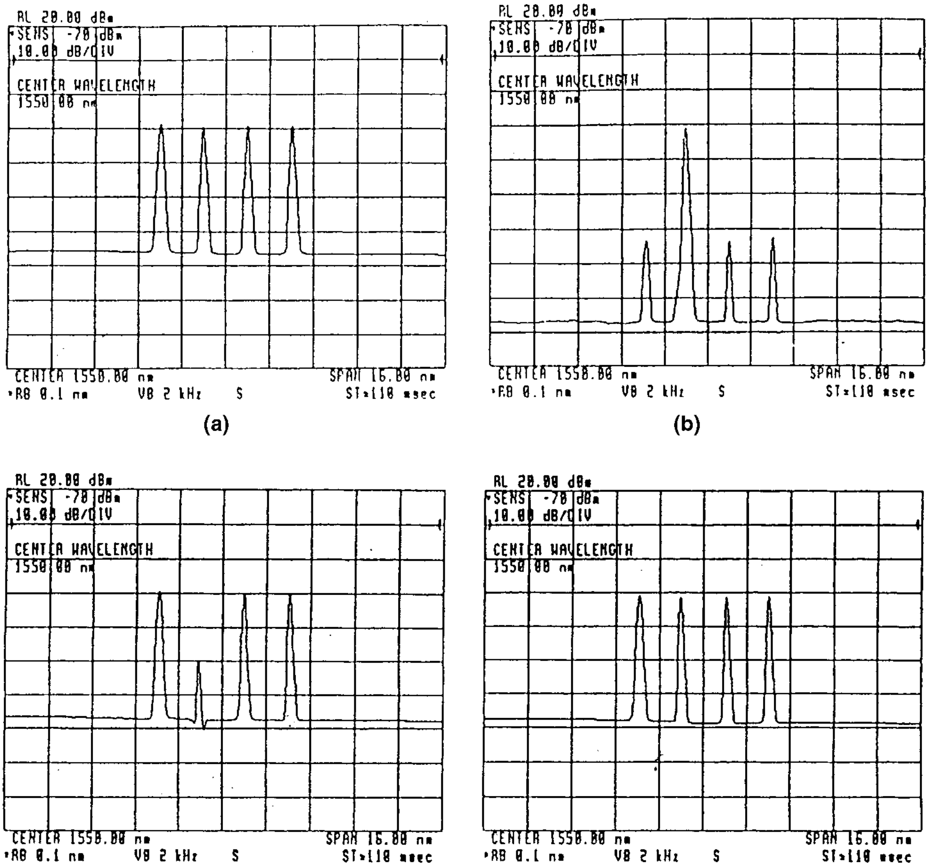


Figure 2 Experimental setup: EDFA: erbium-doped fibre amplifier, VA: variable attenuator. SMF: simple-mode fibre. PC: polarization controller. RX: optical receiver. OPBF: optical bandpass filter. BERT: BER test set.

ITU draft standard of 200 GHz (1.6 nm) channel spacing with central wavelengths of 1547.7, 1549.3, 1550.9, and 1552.5 nm are used and externally modulated with a 2.5 Gbs^{-1} non-return-to-zero (NRZ) format. Four polarization controllers (PCs) are used to adjust the polarization of the DFB lasers to match the LiNbo$_3$ intensity modulator. A total of 100-km standard SMF is used as the transmission link. Two erbium-doped fibre amplifiers (EDFAs) with a saturated output power of $+13.5$ dBm and noise figures of less than 5 dB are employed to provide the required power to compensate for the fibre loss. An optical bandpass filter (BPF) with 3-dB bandwidth of 1.0 nm and an insertion loss of 2.4 dB was located at the receiving end to select the WDM channel for signal detection. A PIN FET receiver with a sensitivity of -32.5 dBm at bit-error-rate (BER) of 1×10^{-9} was used to investigate the BER performance. The averaged add/drop/pass-through insertion losses of this WADM device are all about 3.7 dB, which resulted from the insertion losses of the OSW pair, two OCs and FBGs. The isolation of each OC is about 50 dB. The 3-dB bandwidth and reflectivity of the FBGs are 0.25 nm and 99%, respectively.

4. Experimental results and discussion

Figure 3 shows the signal spectra of: (a) the four-ITU-WDM-channel input signals, (b) the dropped signal, (c) the passed-through signals, and (d) the added output-signals exiting WADM when the OSWs are connected to the FBG$_2$ with a central reflective wavelength of 1549.3 nm. Three small spectral components contaminating the drop in Fig. 3b may be due to the back reflection of the OC1 and all connectors. The WADM also induces crosstalk component at the passing-through channel. The WADM induces crosstalk to both the dropped channel and passing-through channel. The issues of crosstalk-induced power penalty are studied somewhere else [9, 10] for both homodyne and heterodyne



(a) (b)

(c) (d)

Figure 3 Power spectra of (a) the four-WDM-channel input signals, (b) the dropped signal, (c) the passed-through signals, and (d) the output signals including a new added signal when the OSWs are connected to the FBG_2 with reflective wavelength of 1549.3 nm.

crosstalk. It is found experimentally that the WADM has not induced crosstalk for too large a penalty to our system.

The −32 dB crosstalk originating from the dropped channel represents homodyne crosstalk have the same wavelength as that of the added channel at the WADM output. Even using the worst-case Gaussian approximation to analyse homodyne crosstalk, the system can tolerate a crosstalk level of −25 dB for a power penalty less than 1 dB. The −21 dB crosstalk originating from the pass-through channels represents heterodyne crosstalk having different wavelength with the dropped channel. WDM channel can tolerate more than −15 dB of heterodyne crosstalk for a power penalty less than 0.5 dB at BER of 10^{-9}. Therefore, the crosstalk levels in our WADM do not degrade the system performance as verified by experimental demonstration.

Although the experiment for two-channel WADM is not demonstrated because of our resource, the result of the add/drop channel reflected once by one FBG (λ_i as in fig. 2b) should be similar to that of one-channel add/drop. For the add/drop channel reflected twice by two FBGs (λ_2 as in Fig. 2b) with the same reflective wavelength, the FBGs must be chosen to have identical central reflective wavelength. Note that a small wavelength offset between the central wavelength of FBGs or misalignment between the DFB laser and the FBG may induce a large power penalty and signal level degradation. Misalignment of ±0.1 nm will induce a 0.5 dB power penalty and a 1.2 dB signal level degradation by the FBGs used in our experiment. In the two-channel add/drop, the circulator-grating combination exhibited a total insertion loss of about 1.2 dB larger than that of one-channel add/drop because one more inter-port insertion loss should be accounted for in the former case. Figure 4 shows the BER performance at 1549.3 nm versus the received channel power for back-to-back (0 km), drop (50 km), drop-and-re-add (100 km), and pass-through (100 km) at the 1550.9-nm channel. Note that a negligible power penalty of only 0.3 dB is observed in this $2.5\,\mathrm{Gbs}^{-1} \times 4$ channel of 100-km network demonstration. The demonstration of system performance confirms the feasibility of the proposed WADM.

The WADM can be improved for the following factors: low channel crosstalk, uniform and low channel loss, and low cost. The channel crosstalk can be reduced to be smaller than −50 dB by using ultra-high-reflectivity (~100%) FBGs and low-back reflection (less than −60 dB) components, and angled physical contact (APC) connectors. The low and uniform loss characteristics of 3.7 dB can be achieved for all add/drop/pass-through channels due to the nearly spectral independent loss of the OSWs and OCs. The low and uniform loss characteristic of this WADM provides the feasibility of cascading large number of WADMs in the optical networks. Also, because of successful development and mass production of FBGs and other components such as OSWs and OCs, the WADM will be of potentially lower cost than that of other AWG- or AOTF-based WADM devices. While replacing the linear FBGs with chirped FBGs in the WADM, the add/drop functionality with dispersion compensation [11] can be simultaneously realized. It may find

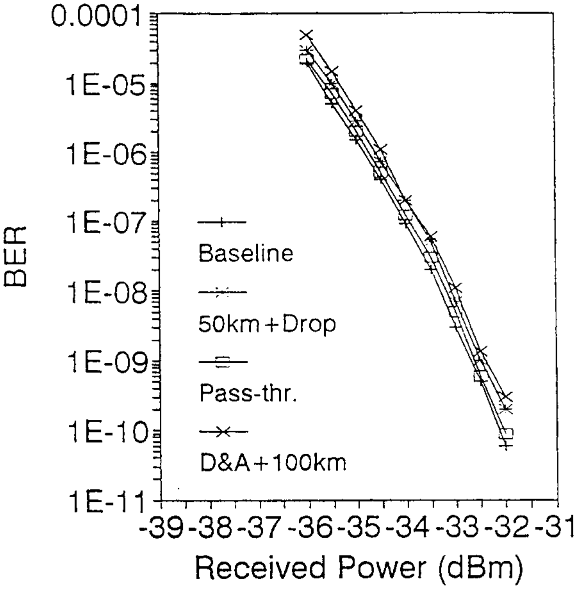


Figure 4 Measured BER performance of the WADM at 1549.3 nm against the received power for back-to-back (0 km), drop (50 km), drop-and-re-added (100 km), and pass-through (100 km) at 1550.9 nm cases.

potential applications in high-speed WDM networks with a data rate of 10 Gbs^{-1} per channel. Furthermore, after minor rearrangement of this WADM, a wavelength-tunable and selective WDM cross-connect can be implemented [12].

5. Conclusion

In summary, one- and two-channel reconfigurable WADMs based on FBGs and OSWs are proposed. A one-channel add/drop WADM is demonstrated in 2.5 $\mathrm{Gbs}^{-1} \times 4$ WDM-channel for a fibre distance of 100 km. The functions of drop, re-add and pass-through are demonstrated with a negligible power penalty at about 0.3 dB when compared to back-to-back transmission. The proposed WADM with features like low channel crosstalk, low and uniform channel insertion loss, and low cost may make these devices improve the survivability and provide more reconfigured flexibility in WDM networks.

Acknowledgements

The authors would like to thank Dr. Y.-K. Tu and J.-W. Liaw of Chung-Hwa Telecommunication Laboratories, Taiwan for helpful discussion. The work was partially supported by Grant No. NSC-087-2215-E-009-012 from the National Science Council, Taiwan, ROC.

References

1. A. F. ELREFAIE, E. L. GOLDSTEIN, S. ZAIDI and N. JACKMAN, *IEEE photon. Technol. Lett.* **5** (1993) 1026.
2. Special Issue on Multiwavelength Optical Technology and Networks, *J. Lightwave Technol.* **14** (1996).
3. M. J. CHAWKI, L. BERTHOU, E. DELEVAQUE, E. GAY and L. LEGAC, 1995 Proceedings of 21st *ECOC'*95, 1995, Paper MoA.3.7.
4. O. ISHIDA, H. TAKAHASHI, S. SUZUKI and Y. INOUE, *IEEE Photon. Technol. Lett.* **6** (1994) 1219.
5. K. OKAMOTO, K. TAKIGUCHI and Y. OHMORI, *Electron. Lett.* **31** (1995) 723.
6. K. W. CHENG, J. *Select. Areas Commun.* **8** (1990) 1015.
7. H. OKAYAMA, Y. OZEKI, T. KAMIJOH, C. Q. XU and I. ASABAYASHI, *Electron. Lett.* **33** (1997) 403.
8. S -K. LIAW, Y.-K. CHEN and C.-C. LEE, *OFC'*98, San Jose, CA, USA, 1998, Paper WM39.
9. K.-P. HO. C.-K. CHAN, F. K. TONG and L. K. CHEN, *IEEE Photon. Tech. Lett.*, **10** (1998) 457.
10. K.-P. HO and S.-K. LIAW, *IEEE Photon. Technol. Lett.* **10** (1998) 737.
11. A. D. ELLIS, R. KASHYAP, I. CRISP and D. J. MALYON, *Electron. Lett.* **33** (1997) 1474.
12. Y.-K. CHEN, S.-K. LIAW and C.-C. LEE, *CLEO'*98, San Francisco, CA, USA, 1998, Paper CWT4.