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LETTER

Formulation of Waveguide Connection for Waveband MUX/DEMUX Using Concatenated Arrayed-Waveguide Gratings

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SUMMARY Recently we proposed a new waveband MUX/DEMUX that uses two concatenated cyclic AWGs. We analyse and formulate connection arrangements of the waveguides connecting the two AWGs. The port utilization of the device is shown to be 100% with bi-directional input fibers.

key words: *waveband, waveband filter, AWG, MUX/DEMUX*

1. Introduction

Broadband access is being rapidly adopted throughout the world and, as a result, traffic is continually increasing. Further traffic expansion will occur in the near future with the introduction of new broadband services including IP video and HDTV, which will warrant the introduction of the hierarchical optical path cross-connect (HOXC) [1]–[3]. Hierarchical optical paths have been shown to decrease the total cost of optical cross-connects [4]. To realize the HOXC one key component is the waveband (a group of wavelength channels in DWDM) multi/demultiplexer (WB MUX/DEMUX). A thin-film filter has been reported that offers 8-skip-0 band operation supporting a total of 32 channels at 100-GHz spacing [5]. Other waveband-filters based on arrayed-waveguide gratings (AWG) have been reported. They realize an 8-skip-0 band configuration with a total of 40 channels and 100-GHz spacing [6]. A more recent proposal [7] uses concatenated cyclic AWGs to realize the WB MUX/DEMUX. The key to the WB MUX/DEMUX is that it retains multi/demultiplexing granularity at the individual wavelength channel level while outputting the WBs at different ports. This means that conventional AWGs that have wavelength channel resolution on the ITU-T grid can be utilized. The salient feature of the proposed WB MUX/DEMUX is that it can accommodate multiple input fibers simultaneously and demultiplex each band to different output ports. In [7], some possible connection arrangements of the two AWGs were demonstrated. In this paper we developed the formulations of two AWG concatenation arrangements for the first time. The connection patterns include one that eliminates all waveguide crossing in connecting the two AWGs, while the other one maximizes MUX/DEMUX port utilization efficiency.

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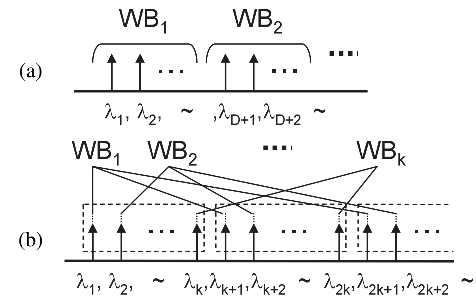

Fig. 1 Two WB arrangements.

2. Waveband Arrangement

There are two different WB arrangements [7]. The first one, a conventional arrangement, is the continuous wavelength path arrangement shown in Fig. 1(a). The other offers the interleaved wavelength path arrangement depicted in Fig. 1(b). From the networking point of view, the WB arrangement has virtually no effect on network provisioning or OA&M (Operation, Administration and Maintenance).

3. Formulation of Port Connections of Two AWGs in Proposed WB MUX/DEMUX

In a cyclic AWG with M input and M output ports, the output port number (# output port) for each pair of wavelength number (# wavelength) and input port number (# input port) is determined by

$$\text{\# output port} = (\text{\# wavelength} - \text{\# input port})_{\bmod M} + 1 \quad (1)$$

Here, cyclic means that the free spectral range (FSR) of the $M \times M$ AWG equals to the width that covers M channels. In this paper, we use cyclic AWGs that hold this input-output relation. We exploit the cyclic nature of AWGs in our WB MUX/DEMUX that uses concatenated cyclic AWGs. There are several possible variations for a pair of AWGs, and the most fundamental and effective ones are discussed hereafter; variations that introduce additional AWG ports are not considered. Let M be the total number of wavelength paths per fiber, B the number of WBs per fiber, and D the number of wavelength paths per WB. Hence, the product of B and D equals M. λ_1^A and WB_1^A represent wavelength path 1 in fiber A and WB 1 in fiber A, respectively. Input side AWG is denoted as AWG X and output side AWG as AWG Y, xa (ya) represents the number a input port of AWG X (Y), and the Xa (Ya) represents the number a output port of AWG X (Y) (see Fig. 2).

3.1 Continuous WB Arrangement

Let k-th waveband WB_k ($k = 1, \cdots, B$) accommodate D wavelength paths $\lambda_{kD+1}, \cdots, \lambda_{(k+1)D}$. Suppose that we have AWG X and AWG Y whose sizes are $M \times M$ and $N \times N$ ($N \geq M + B$), respectively. In this case, proposed WB MUX/DEMUX is realized by the following connections between # X_{out} of AWG X and # y_{in} of AWG Y:

$$\#y_{\text{in}} = \#X_{\text{out}} + j\,[(\#X_{\text{out}} - 1)\,/D] + i$$
$$(1 \leq \#X_{\text{out}} \leq M, \quad 1 \leq \#y_{\text{in}} \leq N) \tag{2}$$

where $[z]$ is the largest integer such that $[z] \leq z$, and i, j are integers satisfying the following relations,

$$i + j(B - 1) + DB \leq N, \quad i \geq 0, j \geq 1 \tag{3}$$

Input fiber connection ports to AWG X can be determined as

$$\#x_{\text{in}} = 1 + sD \quad (1 \leq \#x_{\text{in}} \leq M) \tag{4}$$

where s is an integer satisfying the following relation

$$0 \leq s \leq B - 1 \tag{5}$$

Please note that multiple input fibers that satisfy Eq. (4) can be accommodated. With AWG X the size of which is larger than M, it is possible to create a WB MUX/DEMUX that can multi/demultiplex WBs, however, port usage is degraded and so it is not discussed hereafter. Figure 2 shows an example of our proposed MUX/DEMUX where M, B, D, and N equal 16, 4, 4, and 20, respectively. Parameters i and j are set at 0 and 1, respectively. It should be noted that the continuous WB arrangement can eliminate all waveguide crossing between the two AWGs, which is very attractive for the monolithic realization of the MUX/DEMUX via PLC (Planar Lightwave Circuit) technologies. The results of the monolithic realization are presented in [8]. With this arrangement, there are some unused AWG Y ports.

3.2 Interleaved WB Arrangement

Let the k-th waveband WB_k ($k = 1, \cdots, B$) accommodate D wavelength paths $\lambda_k, \lambda_{k+B}, \cdots, \lambda_{k+(D-1)B}$. Suppose that we have AWG X and AWG Y whose sizes are both $M \times M$. In this case, the proposed MUX/DEMUX is realized by the following connections between the two AWGs:

$$\#y_{\text{in}} = \{B\,(2\,[(\#X_{\text{out}} - 1)\,/B] + 1) - \#X_{\text{out}} + h\}_{\bmod M} + 1$$
$$(1 \leq \#X_{\text{out}} \leq M, \quad 1 \leq \#y_{\text{in}} \leq M) \tag{6}$$

where $[z]$ is the largest integer such that $[z] \leq z$, and h is integer satisfying the following relation

$$0 \leq h \leq M - 1 \tag{7}$$

Input fiber connection ports to AWG X can be written as

$$\#x_{\text{in}} = (2gB + f)_{\bmod M} + 1 \quad \text{or}$$
$$= (2gB + f + e)_{\bmod M} + 1 \quad (1 \leq \#x_{\text{in}} \leq M) \tag{8}$$

where g, f, and e are integers satisfying the following relations

$$g \geq 0, \quad 0 \leq f \leq 2B - 1, \quad e = 1, 3, \cdots, 2B - 1 \tag{9}$$

When both AWG X and Y are larger than $M \times M$, our proposed WB MUX/DEMUX can multi/demultiplex WBs, too.

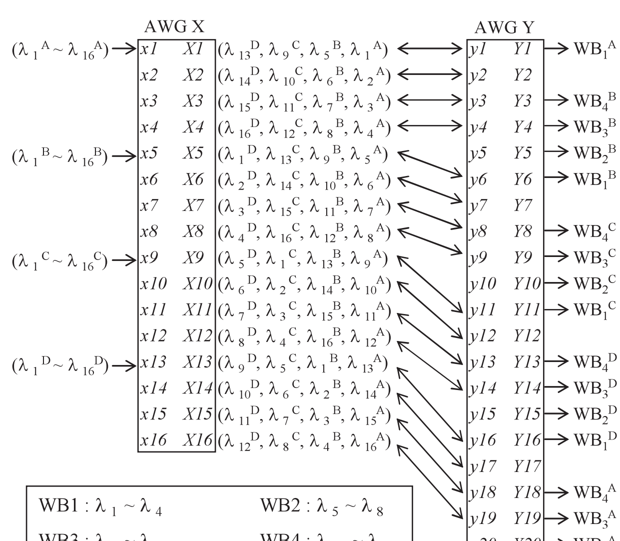

Fig. 2 WB MUX/DEMUX with continuous WB arrangement.

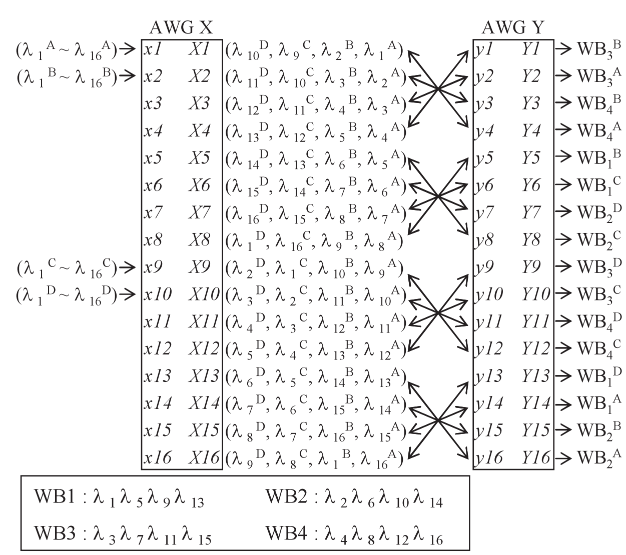

Fig. 3 WB MUX/DEMUX with interleaved WB arrangement.

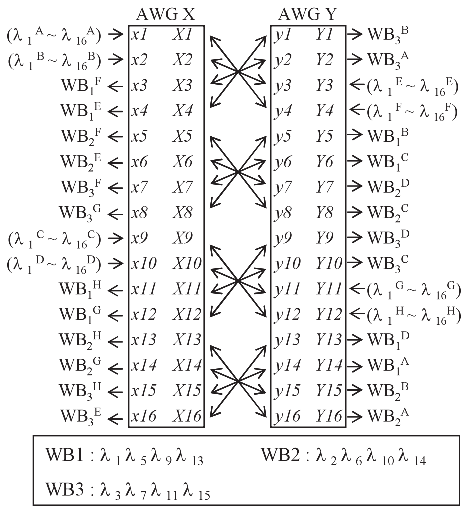

Fig. 4 WB MUX/DEMUX for multiple bi-directional input fibers with interleaved WB arrangement.

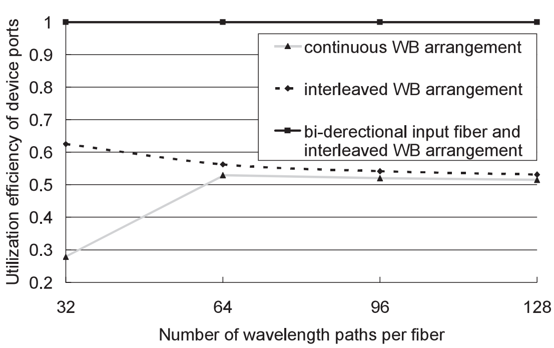

Fig. 5 Utilization efficiency of device ports.

However, port usage is degraded and hence it is not discussed hereafter. Figure 3 shows an example of our proposed MUX/DEMUX where M, B, and D equal 16, 4, and 4 respectively. The parameters h, f, and e are set at 0, 0, and 1, respectively. Compared to the continuous waveband case, this interleaved WB arrangement can enhance AWG port usage because there is no unused AWG Y port.

Furthermore, this MUX/DEMUX permits the connection of multiple bi-directional input fibers. This can maximize the utilization efficiency of the input and output ports of the AWGs. For example, in additional to four input fibers that are connected to AWG X, other four input fibers can be connected to AWG Y port $Y3$, $Y4$, $Y11$, and $Y12$, and each WB on the AWG Y input fibers is split and outputs from AWG X port xi as shown in Fig. 4. Please note that with this arrangement, a WB consisting of λ_4, λ_8, λ_{12}, and λ_{16}, cannot be used. This restriction can be removed by using optical circulators. The circulators, which are not shown in Fig. 4, can be placed to service ports, $x1$, $x2$, $x9$, $x10$, $Y3$, $Y4$, $Y11$, and $Y12$. Figure 5 shows the utilization efficiency of the device ports that is defined as the ratio of number of used ports to total port number of AWG X_{in} and Y_{out} ports. Here, the number of wavelength paths is changed and that of WBs is set at 8.

4. Conclusions

We developed formulations for connecting waveguides between the two AWGs in a recently proposed WB MUX/ DEMUX. The device can be shared by multiple input fibers, and the port utilization of the device was shown to be 100% with bi-directional input fibers. This is very effective in creating a cost effective and small size WB cross-connects.

Acknowledgment

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