Highly rectangular SCL-band MUX/DEMUX filter using compact cascaded arrayed waveguide gratings

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Abstract: We propose a small-footprint arrayed-waveguide grating (AWG) design method in which an arrayed waveguide area serves as an evaluation metric and report a 170-nm-wide and highly rectangular waveband MUX/DEMUX filter using compact cascaded AWGs. © 2024 The Author(s)

1. Introduction

Network traffic is growing at a rate of approximately 30% per year, and transceiver baud rates continue to increase accordingly. In fiber optic communications, it is envisioned that the transmission capacity per single wavelength band will be saturated despite the increasing trend toward higher baud rates. For example, in C-band transmission, a transmission capacity of 75 GHz spacing at 400 Gbps with 64 channels is equivalent to that of 150 GHz spacing at 800 Gbps with 32 channels. Therefore, multiband transmission systems have been developed to expand transmission capacity [1,2]. As shown in the referred papers, it is reasonable to use different fiber amplifiers for each wavelength band in a multiband system because the rare-earth-doped fiber amplifiers are changed for each wavelength band. Note that since the gain bands of fiber optic amplifiers in adjacent wavelength bands overlap, it is ideal to utilize wavelength bands continuously [3,4]. To achieve this, when an optical MUX/DEMUX filter is used to divide the multiband into single wavelength bands, the boundaries between the bands should be as narrow as possible. In addition, since the proportion of the single-channel bandwidth to the wavelength band is increasing as the baud rate increases, maximizing the number of transmission channels by utilizing band boundaries without waste is effective in increasing transmission capacity.

Ultra-wideband and rectangular-spectrum optical MUX/DEMUX filters have been developed for decades in the fields of free-space diffraction gratings [5–8], dielectric multilayers [9], and integrated waveguides [10–12]. Free-space-based filters using diffraction gratings and spatial light modulators (SLMs) can be used to develop high-resolution tunable wavelength filters; however, their operating bandwidth is determined by the areas of SLMs, and their insertion loss tends to be higher than other configurations. Although dielectric thin film optical filters have low-loss characteristics, they are unsuitable for specific cases where optical signals are divided into multiple ports due to an increase in loss with the number of ports. Waveguide-type passive filters can be mass-produced by integration on wafers, and the number of ports can be increased without insertion-loss degradation. In particular, an arrayed waveguide grating (AWG) is widely used as a waveguide (de)multiplexer because it can form a multi-channel optical wavelength filter with low loss [13].

To develop wide-band filters, the free spectral range of an AWG must be widened by reducing the path length difference between adjacent arrayed waveguides. In short-path-length-difference AWGs, typically configured with two straight waveguides and one bent waveguide [14], the gap between arrayed waveguides is small, and propagating lightwaves are affected by adjacent waveguides through mode coupling, resulting in significant phase errors. To solve this problem, several design methods for short-path-length-difference AWGs with relatively small footprints have been proposed [15–17]. However, previous studies have not adequately discussed footprint minimization. This is because the reported design methods derive structural parameters of arrayed waveguides under conditions that can be solved through simple matrix calculations. In this paper, we propose a smaller-footprint AWG design method in which the arrayed waveguide area is used as an evaluation metric and report a highly rectangular SCL-band optical MUX/DEMUX filter using compact cascaded AWGs.

2. Highly rectangular SCL-band MUX/DEMUX using cascaded AWGs

Cascaded AWGs are one of the configurations that can achieve a highly rectangular transmission spectrum for waveguide optical filters [10]. Figure 1 illustrates a SCL-band MUX/DEMUX filter using cascaded AWGs: a wavelength band is sampled with high resolution at the left AWG, and the sampled optical waves are multiplexed to each port at the right AWG. In the equal-path-length array connecting the two AWGs, the waveguide connecting positions to the right AWG are adjusted for each band. To develop a highly rectangular optical wavelength filter, it is important to cascade AWGs with a wide band and high resolution. Increasing the wavelength resolution of AWGs

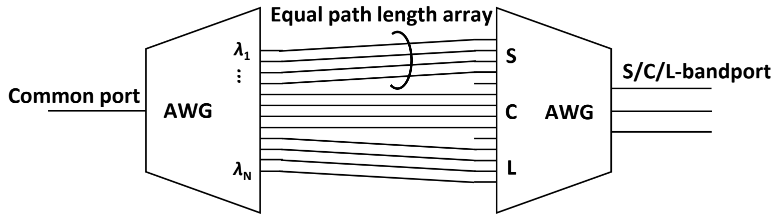

Fig. 1 Schematic illustration of a SCL-band MUX/DEMUX filter using cascaded AWGs.

results in a greater number of arrays and a longer slab length. However, wavelength sampling causes ripples in merged spectra. These ripples can be suppressed by setting the mode field diameter at a junction between the slab end and the equal-path-length waveguide array to be sufficiently wider than the equal-path-length array waveguide mode fields [10]. We use the configuration shown in Fig.1 for the highly rectangular SCL-band MUX/DEMUX filter. In the following sections, we propose a method to minimize the AWG footprint and describe a specific design and experimental results of the filter.

2.1. Small-footprint AWG design

An S-shape AWG configuration was reported as a small-footprint design technique with a wide wavelength range and a short path length difference [17]. However, its major drawback is the additional path length which increases the area of arrayed waveguides. This additional path length is introduced to prevent waveguide overlap and is not related to its functionality and performance. Figure 2 shows a schematic illustration of our proposed AWG design. To flatten the transmission spectrum of cascaded AWGs, we set the left and right slab lengths to different values. The proposed configuration consists of three blocks (left, center, and right), and it is not necessary to set the path length difference constant for each block. The AWG consists of N arrayed waveguides and two slab waveguides, and the path length of the i-th $(1 \leq i \leq N)$ waveguide is adjusted by the sum of the three blocks. The path length difference between the arrayed waveguides for each block is given a degree of freedom to reduce redundant paths; the continuity of the waveguides in the XY plane and the gaps between the waveguides of the i-th array in each block are constrained. The evaluation metric for the arrayed waveguide area $\boldsymbol{A}$ is given by

$$\boldsymbol{A} := Y_1(X_{L1} + X_C + X_{R1}) + \sum_{i=2}^{N} D_i(X_{Li} + X_C + X_{Ri}) \qquad (1)$$

where X_{Li}, X_C and X_{Ri} are the widths on the X-axis of the left, center, and right blocks, respectively; Y_1 is the height of the innermost array waveguide of the left block. The waveguide distance d at the boundary between the left (or right) and center block is set to be the desirable constant value. For simplicity, X_C is kept constant regardless of i. X_{L1}, X_{R1}, and Y_1 are obtained by determining the number and pitch of the arrayed waveguides, the slab lengths, and the minimum radius of the bending waveguide. X_{Li}, X_{Ri}, X_C, and D_i can be expressed simply using the structural parameters of the waveguides (shown in Fig. 2) and trigonometric functions. The structural parameters can be obtained analytically by minimizing $\boldsymbol{A}$ and defining constrains determined by fabrication process conditions.

2.2. Cascaded AWG filter design

To develop a highly rectangular SCL-band optical MUX/DEMUX filter, we designed an AWG that samples a wavelength range of 170 nm (21.15 THz) at 150 GHz using silica waveguides having a refractive index difference of

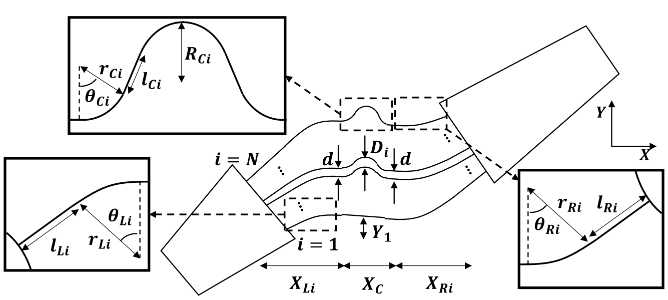

Fig. 2 Proposed design of the small-footprint arrayed waveguide grating.

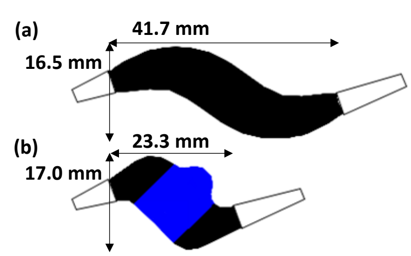

Fig. 3 Design comparison between (a) S-shape and (b) proposed AWGs using common AWG parameters. In (b), the waveguides in the center block are drawn in blue.

1.5%. Figure 3 shows the design comparison between the S-shape and proposed-shape AWGs. Our proposed design can reduce the arrayed waveguide area to 58% of that in the S-shape design. In Figure 3, the slab lengths are intentionally different from each other to adjust the optical field diameter of the AWG termination; ripples in the transmission spectra can be suppressed as previously mentioned. The diffraction order of the AWG, the number of the arrayed waveguides, and the ratio of the slab waveguide lengths was set to 6, 500, and 2, respectively. The left and right AWGs were connected band by band with 150 equal-path-length waveguides. The resulting footprint of the filter is approximately 115×22 mm^2.

2.3. Measurement of cascaded AWG filter spectra

The designed filter was fabricated using silica-based planar lightwave circuit technology including a precise inspection technique [18]. The transmission spectra were evaluated in the chip state experimentally. Figure 4 shows the measured transmission spectra of the fabricated waveband MUX/DEMUX filter. We obtained excellent optical characteristics for the insertion loss, 15-dB guard-band and isolation with confirmed values of < 3.7 dB, < 150 GHz and > 35 dB, respectively. The wavelength band boundaries are 1527 and 1568 nm, and the SCL-band with a wavelength range of 170 nm was demultiplexed with highly rectangular spectra.

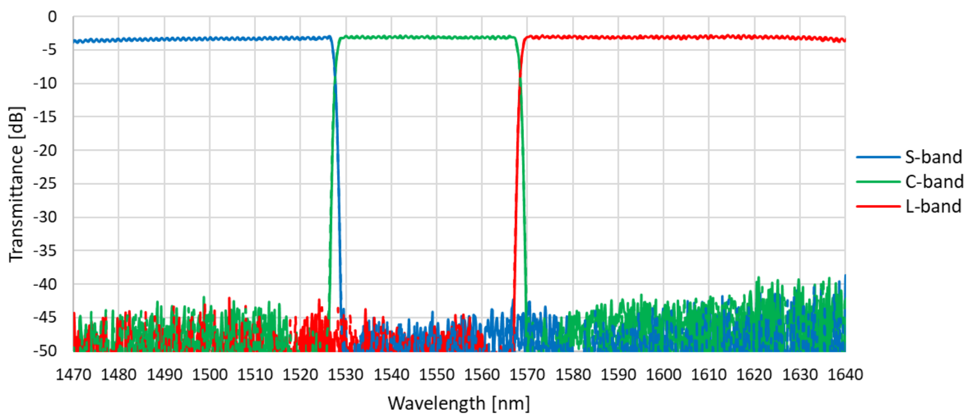

Fig. 4 Experimental results of the transmission spectrum of the fabricated waveband MUX/DEMUX filter using the compact cascaded AWGs. The solid line is drawn in TM mode and the dashed line in TE mode; these lines overlap due to the small polarization dependence (polarization dependent loss < 0.3 dB).

3. Conclusion

We proposed a small-footprint AWG design method in which the arrayed waveguide area serves as the evaluation metric. Our proposed method is versatile and can be applied to any waveguide material and any refractive index difference. We designed and fabricated an SCL-band MUX/DEMUX filter using cascaded AWGs with a refractive index difference of 1.5% and a footprint of 115×22 mm^2. The resulting transmission spectra with an operating wavelength range of 170 nm (21.15 THz), a 15-dB guard band of less than 150 GHz, and an insertion loss of less than 3.7 dB were obtained. Our results show one of the most rectangular spectra among reported waveguide-type filters with an ultra-wide band.

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