Compact and low insertion loss (~ 1.0 dB) Mach-Zehnder interferometer-synchronized arrayed-waveguide grating multiplexer with flat-top frequency response

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Abstract: We have developed a compact Mach-Zehnder interferometer (MZI)-synchronized arrayed-waveguide grating (AWG) multiplexer with 40 100-GHz-spaced channels using 1.5-% Δ waveguides. This MZI-synchronized AWG has a chip size of only 35 x 28 mm^2, and a low insertion loss of 1.0 - 1.2 dB with a flat-top frequency response. This low insertion loss is achieved by i) installing spot-size converters at the ends of optical input and output waveguides, and ii) employing a narrow gap in a directional coupler at the junction of the MZI and AWG. This device exhibited other excellent characteristics including a wide 0.5-dB passband of more than 45 GHz and a low adjacent crosstalk of less than -35 dB.

OCIS codes: (060.1810) Buffers, couplers, routers, switches, and multiplexers; (130.0130) Integrated optics; (130.2755) Glass waveguides

References and links

1. Y. Inoue, "Recent advances in silica-based PLCs," in 2007 IEEE LEOS Annual Meeting Conference Proceedings (IEEE, 2007), paper TuC3.
2. C. R. Doerr, L. W. Stulz, and R. Pafchek, "Compact and low-loss integrated box-like passband multiplexer," IEEE Photon. Technol. Lett. **15**, 918-920 (2003).
3. R. Brainard, B. Fondeur, and D. J. Dougherty, "Advances in planar lightwave circuits for wavelength routing applications," in Technical Digest of Integrated Photonics Research and Applications Nanophotonics 2006 (Optical Society of America, 2006), paper IMB1.
4. B. Fondeur, R. Brainard, D. Dougherty, and J. Bhardwaj, "Advances in PLC technology for DWDM applications," in Proceedings of 32nd European Conference on Optical Communication (ECOC) 2006 (Société de l'Electricité, de l'Electronique et des Technologies de l'Information et de la Communication, 2006), paper Tu4.4.1.
5. A. Sugita, A. Kaneko, K. Okamoto, M. Itoh, A. Himeno, and Y. Ohmori, "Very low insertion loss arrayed-waveguide grating with vertically tapered waveguides," IEEE Photon. Technol. Lett. **12**, 1180-1182 (2000).
6. M. Itoh, T. Saida, Y. Hida, M. Ishii, Y. Inoue, Y. Hibino, and A. Sugita, "Large reduction of singlemode-fibre coupling loss in 1.5% Δ planar lightwave circuits using spot-size converters," Electron. Lett. **38**, 72-74 (2002).
7. B. Jacobs, R. Zengerle, K. Faltin, and W. Weiershausen, "Vertically tapered spot size transformers by a simple masking technique," Electron. Lett. **31**, 794-796 (1995).
8. T. Mizuno, T. Kitoh, M. Itoh, T. Saida, T. Shibata, and Y. Hibino, "Optical spotsize converter using narrow laterally tapered waveguide for planar ligtwave circuits," J. Lightwave Technol. **22**, 833-839 (2004).

1. Introduction

Arrayed-waveguide gratings (AWGs) constructed using silica-based planar lightwave circuit (PLC) technology are now playing an important role in rapidly growing dense wavelength division multiplexing (DWDM) systems in both long haul and metropolitan networks [1]. In these networks, the systems such as reconfigurable optical add-drop multiplexing (ROADM) systems now require AWGs with a lower loss and a wider passband to realize greater cascadability and higher bit rate transmission. A Mach-Zehnder interferometer (MZI)-synchronized configuration [2], in which an MZI is positioned between input waveguides and a slab waveguide in front of the AWG is an effective way of achieving a low insertion loss and a wide passband in the AWG multiplexers. An insertion loss of 1.5 dB [3] and a 0.5-dB passband greater than 46 GHz [4] have been reported with this configuration.

One drawback of the MZI-synchronized AWG is its increased chip size resulting from the incorporation of the MZI. Although a waveguide with a higher refractive index difference (Δ) can be employed to suppress this chip size enlargement, its use increases the fiber coupling loss, and consequently the insertion loss. Therefore finding a way to achieve a smaller chip size and a lower insertion loss is a serious problem as regards MZI-synchronized AWGs for practical DWDM system applications.

This paper describes the design, fabrication and performance of our compact MZI-synchronized AWG with excellent characteristics including a low insertion loss. We also describe techniques for reducing both chip size and insertion loss.

2. Design and Fabrication of MZI-synchronized AWG

Figure 1 shows the schematic configuration of our MZI-synchronized AWG. The circuit is composed of an MZI and an AWG. A directional coupler (DC) in the MZI is directly connected to the first slab waveguide in front of the AWG. The AWG is designed to have a frequency spacing of 100 GHz and 40 channels. The free spectral range of the MZI is designed to be 100 GHz. We employ high Δ waveguides to realize a small chip size. The Δ and the typical core size of the circuit waveguides are 1.5% and 4.5 x 4.5 μm^2, respectively. A small chip size of 35 x 28 mm^2 including the MZI was achieved. The area of this chip size is less than 40% that of a device in [2] (estimated to be around 85 x 32 mm^2) using conventional 0.65-% Δ waveguides. The circuit was fabricated with our silica-based planar lightwave circuit (PLC) technology; namely a combination of the flame hydrolysis deposition (FHD), photolithography, and reactive ion etching (RIE).

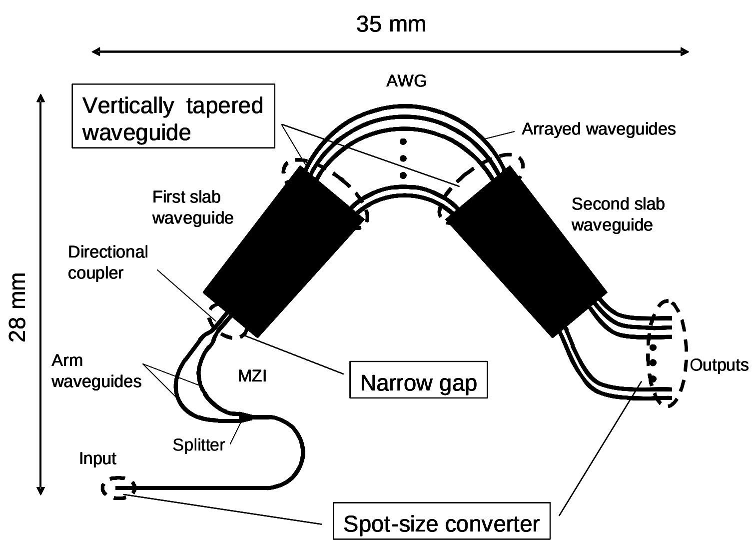

Fig. 1. Schematic configuration of our MZI-synchronized AWG.

We developed two techniques for reducing the insertion loss in our MZI-synchronized AWG. The first involves the use of spot-size converters (SSCs) at the ends of the input and output waveguides to reduce fiber coupling loss. We have proposed a new SSC structure. The second technique employs a narrow gap between the two waveguides in the DC to reduce the mode field mismatch between the input and the output waveguides at the slab edges. The

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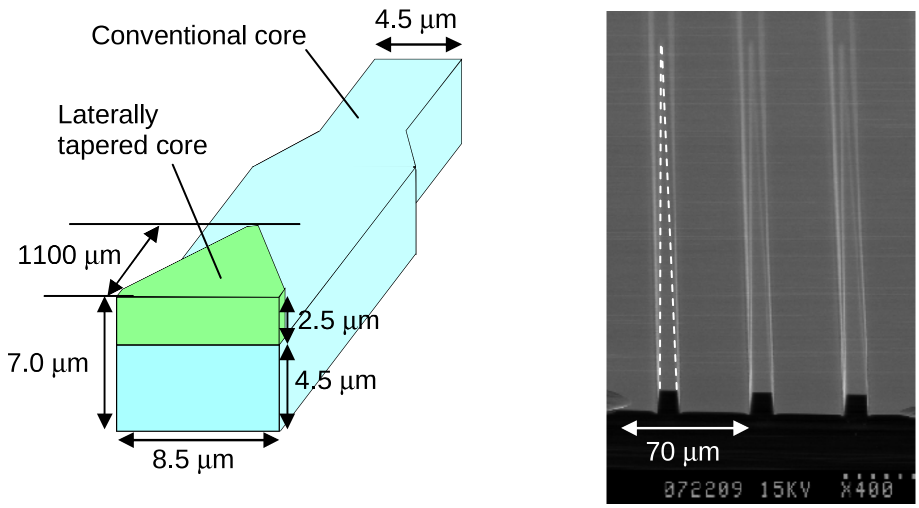
reason why a narrow DC gap is effective for reducing the mode field mismatch is explained later. The positions at which these techniques are used are also shown in Fig. 1. Moreover, we employed a vertical tapered waveguide structure between the arrayed waveguides at the junction of the slab/arrayed waveguides in the AWG [5] to reduce the coupling loss of the slab/arrayed waveguides.

Figures 2(a) and 2(b) are a schematic illustration and a scanning electron microscope (SEM) image of the SSCs used in our MZI-synchronized AWG, respectively. The structure of this SSC is as follows. A laterally tapered core designed to be 1100 μm long and 2.5 μm thick is placed on a conventional core. The lateral taper gradually widens toward the fiber coupling ends so that the mode field of the propagating light in the core enlarges adiabatically and matches that in the fiber. The SSC core at the fiber coupling ends is 8.5 μm wide and 7.0 μm high. These SSC core parameters are selected for coupling to dispersion-shifted fibers (DSFs) in this experiment.

We have already proposed two different types of SSC structure; one has a combined vertically and laterally tapered waveguide [6] fabricated using a shadow etching technique [7], and the other has a narrow laterally tapered waveguide [8]. The shadow etching is a very complicated fabrication process, because it is an etching in an RIE chamber with a shadow mask placed above a wafer. The SSC structure proposed here does not require the shadow etching. Therefore, the new SSC structure is easier to fabricate than the former SSC structure. The latter SSC structure with a narrow laterally tapered waveguide has a very small tolerance as shown in Fig. 3 of [8], because it requires a precise control of a core width to obtain the lowest coupling loss. The new SSC structure, on the contrary, has a large fabrication tolerance because it employs a wide core.

The measured DSF coupling loss of this SSC structure was 0.25 dB per fiber coupling point. This is 0.1 dB/point lower than that of the circuits without SSCs.

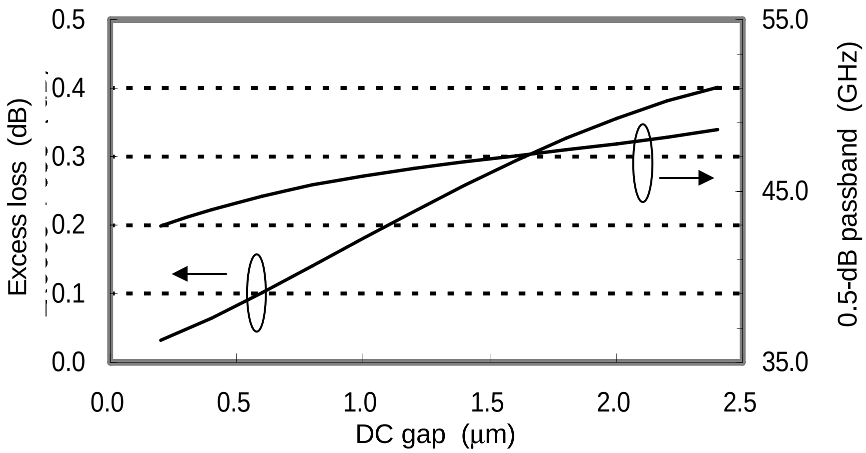


(a) (b)

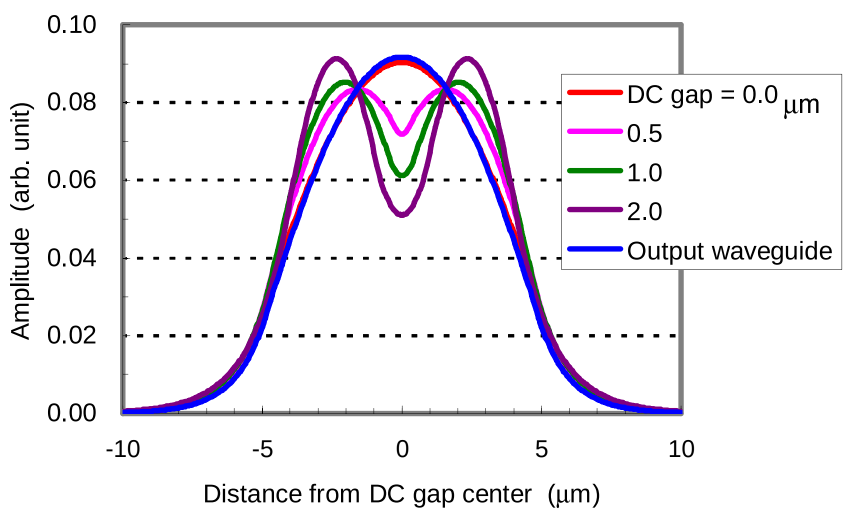
Fig. 2. (a). Schematic illustration of SSCs used in our MZI-synchronized AWG. (b) SEM image of the fabricated SSCs. This image is before embedded with overcladding. Broken lines indicate outlines of the laterally tapered core.

Figure 3(a) shows the result of a numerical calculation indicating the DC gap width vs. the excess loss due to the flattened frequency response at a center wavelength of 1.55 μm. The result of DC gap vs. 0.5-dB passband is also shown. The parameters used in the calculation were a Δ of 1.5%, a waveguide width in the DC of 4 μm, and the width and pitch of the output waveguides at the second slab edge were 10 and 13 μm, respectively.

The excess loss decreases monotonically as the gap becomes narrower. This is explained as follows. The excess loss originates from the field mismatch between an even mode in the DC and a fundamental mode in the output waveguide at the center wavelength. Figure 3(b) shows the calculated even mode fields in DC with various DC gaps. The calculated fundamental mode field in the output waveguide is also shown. The same parameters as those used in Fig. 3(a) were used. As a DC gap becomes narrower, the DC mode field shape varies from double-peak to single-peak and the mode mismatch decreases. Therefore the excess loss decreases.



(a)



(b)

Fig. 3. (a). Numerical calculation results of DC gap width vs. excess loss and 0.5-dB passband in our MZI-synchronized AWG. (b) Calculated mode fields in DC and the output waveguide.

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The 0.5-dB passband also decreases with a narrower DC gap. These results mean that the excess loss and the 0.5-dB passband have a trade-off relationship. We adopted a DC gap of 1 μm taking this relationship into consideration.

3. Optical performance of the device

Figures 4(a) and 4(b) show the complete 40-channel transmittance spectra and their enlarged overlay of the fabricated MZI-synchronized AWG multiplexer. They exhibited a uniform and low insertion loss of 1.0 - 1.2 dB including DSF coupling loss and a low adjacent channel crosstalk of less than -35 dB in a range of the center wavelength ±12.5GHz for 40 channels. They also exhibited a wide 0.5-dB passband of more than 45 GHz for 40 channels. The other characteristics were also excellent, namely a low polarization dependent loss (PDL) of less than 0.15 dB for all channels shown in Fig. 5, and a small chromatic dispersion (CD) of 2 - 6 ps/nm for a center channel (channel No. 21), both in a range of the center wavelength ±12.5GHz.

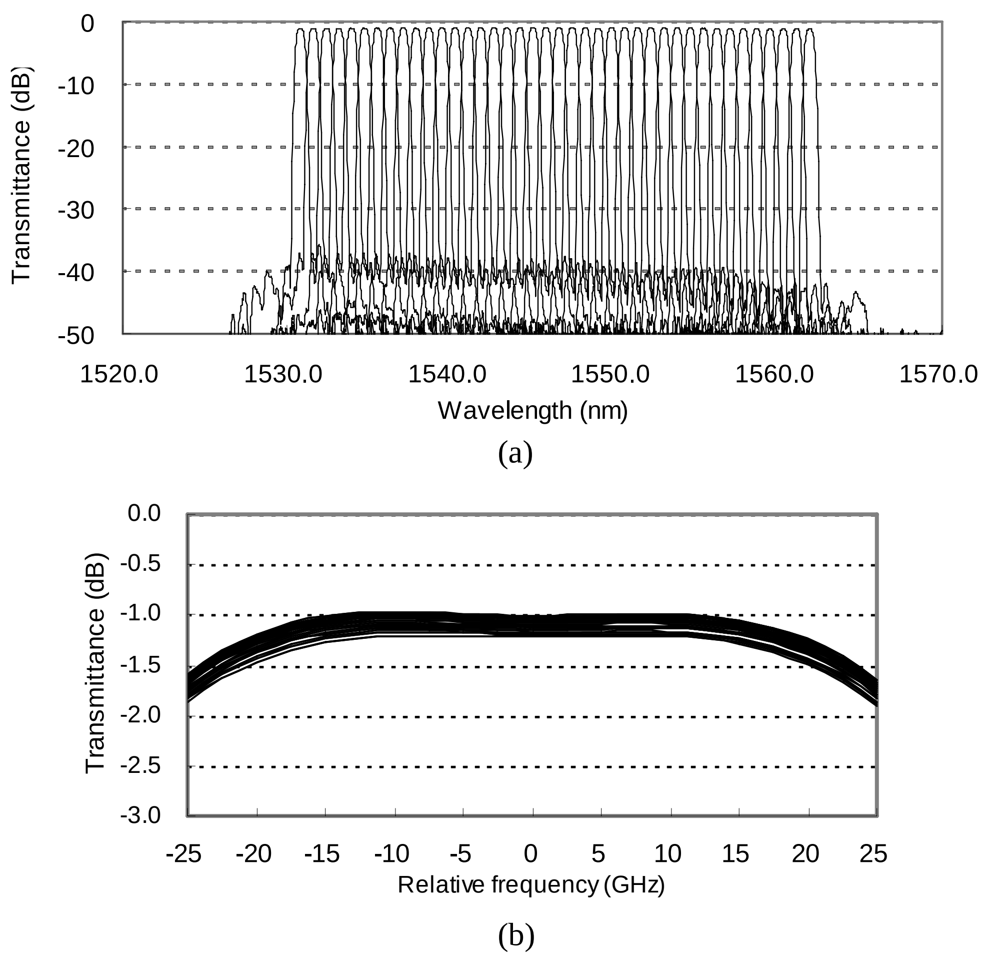

Fig. 4. (a). All 40-channel transmittance spectra, and (b) their enlarged overlay of the fabricated MZI-synchronized AWG.

The items of the total insertion loss of 1 dB were estimated by the results for reference circuit measurement: 0.25 dB/point for the DSF coupling loss as described above, 0.12 dB for the excess loss due to the flattened frequency, and 0.38 dB for the AWG circuit and other excess losses. The obtained excess loss of 0.12 dB for a DC gap of 1 μm agrees well with the estimated value of 0.18 dB shown in Fig. 3(a), which indicates that our design was appropriate.

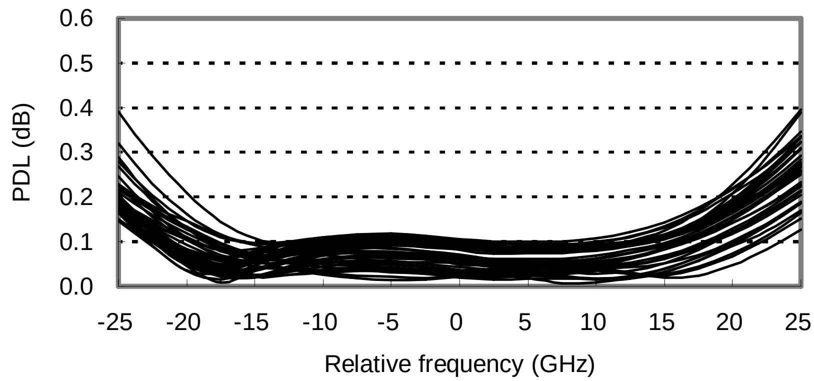

Fig. 5. PDL of the fabricated MZI-synchronized AWG for all 40 channels.

In addition, we estimated a coupling loss between our new SSC and a single-mode fiber (SMF) by calculation. We obtained 0.4 dB/point when the core parameters in our SSC were optimized for SMF coupling. Therefore, a low insertion loss of 1.3 dB is expected for our MZI-synchronized AWG with SMF coupling (1.0 - 0.25 x 2 + 0.4 x 2 = 1.3).

Our performance of the parameters described above, namely the insertion loss, the adjacent cross talk, the 0.5-dB passband, the PDL, and the CD, is better than or almost similar to that reported in [2 – 4].

4. Conclusion

We have developed a compact and low-insertion loss MZI-synchronized flat-top AWG multiplexer with 40 100-GHz-spaced channels. We employed 1.5-% Δ waveguides to realize a small chip size. The chip size was 35 x 28 mm^2 including the MZI, and this is less than 40% of the area of a device using the conventional 0.65-% Δ waveguides. The device exhibits a low and uniform insertion loss of 1.0 - 1.2 dB for all 40 channels including the DSF coupling loss. This low insertion loss was achieved by two techniques. One was to employ new SSCs at the ends of the input and output waveguides to reduce fiber coupling loss. The other was to use a narrow gap in the DC to reduce the excess loss due to the flattened frequency response.

These techniques did not degrade the other optical performance. A wide 0.5-dB passband of more than 45 GHz and a low adjacent crosstalk of less than -35 dB were achieved for all 40 channels. Furthermore, we obtained a low PDL of less than 0.15 dB for all channels and a small CD of 2 - 6 ps/nm for the center channel. These results indicate that performance of our MZI-synchronized AWG is sufficient for practical ROADM system applications.

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