Low-Loss Compact Arrayed Waveguide Grating with Spot-Size Converter Fabricated by a Shadow-Mask Etching Technique

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This paper describes a low-loss, compact, 40-channel arrayed waveguide grating (AWG) which utilizes a monolithically integrated spot-size converter (SSC) for lowering the coupling loss between silica waveguides and standard single-mode fibers. The SSC is a simple waveguide structure that is tapered in both the vertical and horizontal directions. The vertically tapered structure was realized using a shadow-mask etching technique. By employing this technique, the fabricated, 40-channel, 100 GHz-spaced AWG with silica waveguides of 1.5% relative index-contrast showed an insertion-loss figure of 2.8 dB without degrading other optical performance.

Keywords: Arrayed waveguide grating (AWG), optical planar waveguide, spot-size converter, monolithic integration, shadow-mask etching.

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I. Introduction

With an explosive growth of demand for broadband, high-speed, low-cost Internet services, an arrayed waveguide grating (AWG) multiplexer/demultiplexer should be further improved to meet such system requirements as low-cost, small size, and higher channel counts. To these ends, the relative index-contrast Δ of silica channel waveguides increased from 0.75% to 1.5%. The relative index-contrast Δ between the core and cladding of a waveguide is directly related to the size of the integrated planar lightwave circuits (PLCs). Increasing the Δ of waveguides in PLCs reduces the waveguide bending radius and makes it possible to realize compact-sized AWG devices [1]. In our previous work, we used Δ = 0.75% waveguides for fabricating conventional AWG devices with a minimum bending radius of 5 mm in the bent waveguide section. Then, the typical chip size of the AWG with a 100 GHz channel spacing and 40 channel counts was 60 mm × 30 mm. Further increasing the Δ value can reduce the bending radius. For example, if Δ is raised to 1.5%, the bending radius decreases to 2 mm and the size of the 40-channel 100 GHz AWG chip reduces to 27 mm × 24 mm.

However, the insertion loss becomes degraded by the higher coupling loss with a standard single-mode fiber (SMF), which occurs inevitably due to the mode-field mismatch between a silica channel waveguide and an SMF [1]. Several methods of making a spot-size converter (SSC) have been proposed to reduce the fiber-coupling loss [2]-[10]. From the perspectives of process simplification and fabrication tolerance, however, these methods are not adequate. For example, the methods employing a laterally and vertically enlarged tapered waveguide structure require additional processes of patterning, etching, and/or deposition [2]-[4]. The other methods employing a laterally tapered structure with either a large [5] or small [6]-[9] core width or employing a segmented waveguide structure [10] are sensitive to cut-position and/or have a relatively long SSC structure.

In this work, we propose a simple, short SSC that is tapered in both the vertical and horizontal directions. The vertically tapered structure was realized using a shadow-mask etching technique [11] in such a way that the fundamental guided-mode of $\Delta = 1.5\%$ silica waveguides is adiabatically converted to that of an SMF. By using this technique, we fabricated SSCs that are vertically down-tapered and laterally down- or up-tapered. These SSCs were inserted into each region of input/output waveguides in a 40-channel 100 GHz-spaced AWG for reducing the fiber-coupling loss.

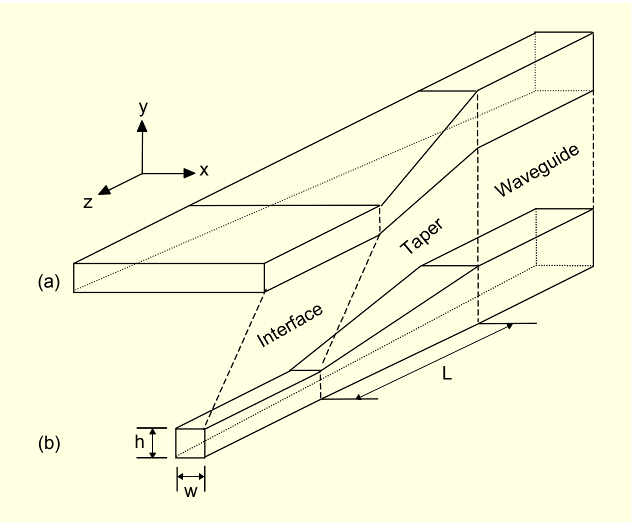

Fig. 1. Schematic diagram of a spot-size converter with the proposed tapered structure. The structure is down-tapered vertically: (a) laterally up-tapered structure and (b) laterally down-tapered structure.

II. Structure of Spot-Size Converters

The structures of the spot-size converter are illustrated in Fig. 1, where the waveguide core is down-tapered vertically. In the lateral direction, it can be either down-tapered or up-tapered for matching the mode-field diameter (MFD) with that of an SMF. The SSC with a tapered waveguide in both the vertical and lateral directions can match the MFD of the planar waveguide with that of an SMF more efficiently than the conventional SSC with a tapered waveguide in only the lateral direction. This is the case when the planar waveguide structure has a very high value of Δ, such as 1.5% in this work.

These structures consist of three regions: a conventional waveguide region, a vertically and laterally tapered region, and a waveguide/SMF interface region. The conventional waveguide structure has an index-contrast of $\Delta = 1.5\%$ with its dimension of $4.5\,\mu m \times 4.5\,\mu m$. In the tapered waveguide region, the core height is gradually decreased (vertically down-tapered), while the core width is gradually increased (laterally up-tapered) or decreased (laterally down-tapered). In either case, the effective-index along the tapered region should be designed to change gradually for adiabatic mode-conversion [12]. The interface region has the role of preventing the tapered region from being cut off during the dicing and polishing processes. In our experiment, the interface region of around 200 μm away from its end-cleaved surface is polished away so that we set it to be 300 μm.

We have calculated the fiber-coupling loss by doing an overlap integral of mode fields between an SMF and the $\Delta = 1.5\%$ silica waveguides with and without the SSC. The field profile inside the tapered waveguide region has been obtained using a two-dimensional finite-difference method. Without the SSC, the fiber-coupling loss was calculated to be 1.52 dB at one coupling-point, which agrees with the measured results shown in Fig. 6.

As shown in Fig. 1, we have considered the following two cases: the waveguide width w of the interface region from 3 to 10 μm for the core height h of 1 μm, and from 1.5 to 5 μm for $h = 2\,\mu m$. The calculated values of the coupling-loss under a quasi-single mode condition were less than 0.4 dB even at the waveguide width of 10 μm when $h = 1\,\mu m$, as shown in Fig. 2. It should be noted that, in either the case of $w < 2\,\mu m$ and $h = 1\,\mu m$ or $w < 1\,\mu m$ and $h = 2\,\mu m$, no guided mode exists in the interface region at a wavelength of around 1550 nm. For the given height of a 2 μm waveguide core, the fiber-coupling loss increases rapidly for $w < 4\,\mu m$, which is quite sensitive to fabrication errors. When $w > 4\,\mu m$, the SSC has no effect on improving the coupling loss. The optimal dimension of the waveguide core at the end of the tapered waveguide region has $h = 1\,\mu m$ and $w = 3\,\mu m$, yielding a fiber-coupling loss of 0.16 dB. However, when $h = 1\,\mu m$, the difference of the coupling loss for different values of w is not large.

The other important parameter is the taper length for adiabatic mode-conversion. As will be explained in the next section, the taper length that can be achieved by the shadow-mask etching technique cannot be made arbitrarily long. Under our experimental conditions, the taper length was limited to be less than 500 μm, as shown in Fig. 5. Hence, the taper should be designed to be as short as possible. For simulating the effect of the taper length on the propagation loss (radiation-coupled loss), we have used a three-dimensional FD-BPM. A linearly

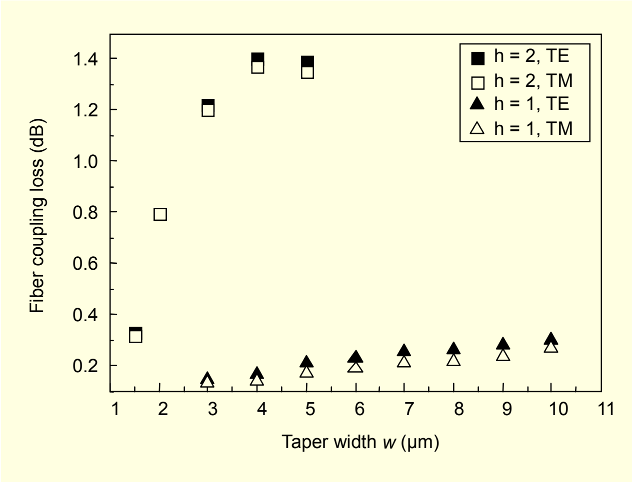

Fig. 2. Calculated fiber-coupling loss versus the cross-sectional dimension under a quasi-single-mode condition.

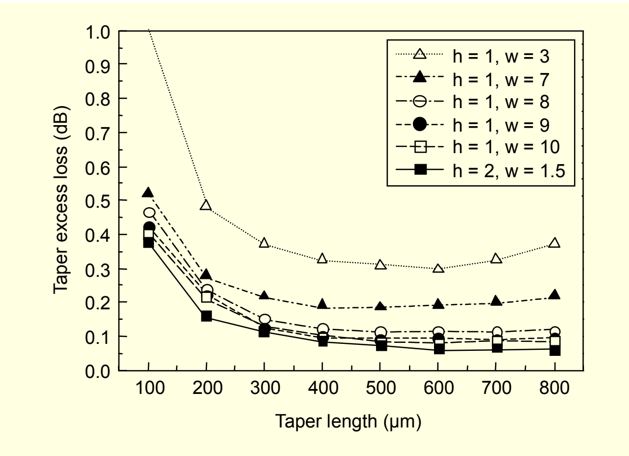

Fig. 3. Calculated taper-excess loss versus the taper length for various waveguide core dimensions.

down- or up-tapered waveguide structure has been assumed in the simulation for simplicity.

The calculated taper-excess loss as a function of the taper length is plotted in Fig. 3. For realistic simulation on the propagation loss, we inserted the 150 μm long interface region into the tapered region. When the taper length is larger than 400 μm, the taper-excess loss is almost unchanged, independent of the SSC structures. Because of the limitation on the taper length, the SSC with h = 1 μm and w = 10 μm, and the SSC with h = 2 μm and w = 1.5 μm show better excess loss behavior than other structures. The total loss should be the sum of the fiber-coupling loss and the taper-excess loss. In the case of the SSC with h = 1 μm and w = 3 μm, the taper-excess loss is too large, even with a lower fiber-coupling loss. Hence, from simulation results, we have obtained the following two optimal combinations of the width and height of the waveguide core at the interface region; w = 9 μm, h = 1 μm, and w = 1.5 μm, h = 2 μm,

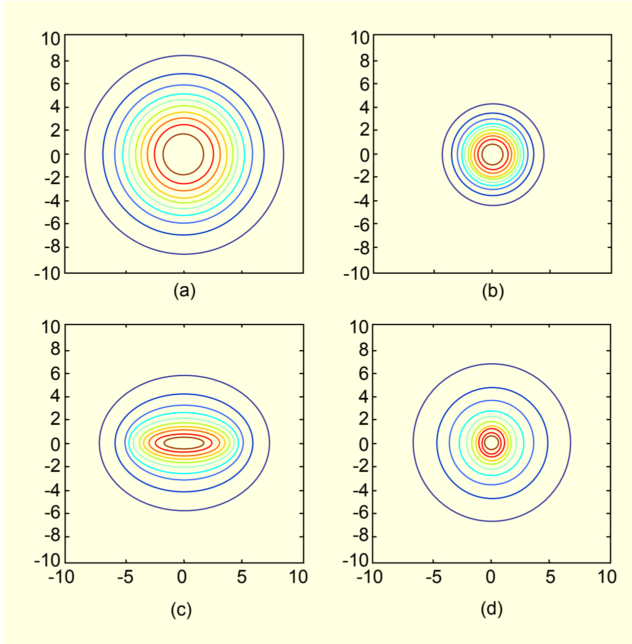

Fig. 4. Contour plots of calculated mode profiles of (a) a standard single-mode fiber, (b) a conventional waveguide with Δ = 1.5%, (c) a laterally up-tapered structure(h = 1 μm, w = 9 μm), and (d) a laterally down-tapered structure (h = 2 μm, w = 1.5 μm).

all with the taper length of 450 μm. This taper length is two or more times smaller than the taper length reported so far.

To confirm the spot-size of the interface region, we calculated the mode-field patterns as the mode field propagates through optimized structures, and compared them with that of an SMF and a conventional waveguide with Δ = 1.5%, which is shown in Fig. 4. Even though the mode field in the SSC with h = 1 μm and w = 9 μm, as shown in Fig. 4(c), is not circularly symmetric, it showed better coupling loss than the SSC with h = 2 μm and w = 1.5 μm, as shown in Fig. 4(d).

III. Experimental Results

We used the so-called silica PLC technology [13] in making the waveguide. All the processes are identical to the standard silica PLC processes, except for the insertion of the shadow-mask etching process before the waveguide patterning processes.

The fabrication steps are as follows. The core layer is prepared by the plasma-enhanced chemical vapor deposition (PECVD) method onto thermally oxidized silicon wafers. Then, the vertically tapered structure is made by the dry-etching of the core layer with a shadow-mask being placed on top of the target core region, as shown in the inset in Fig. 5. In this experiment, the shadow-mask covered the whole area except for the regions of the input/output waveguides. Next,

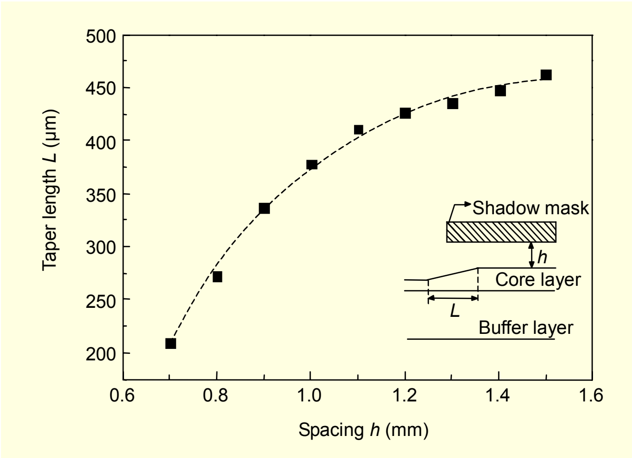

Fig. 5. Measured vertical-taper length versus the spacing between the shadow-mask and the core layer.

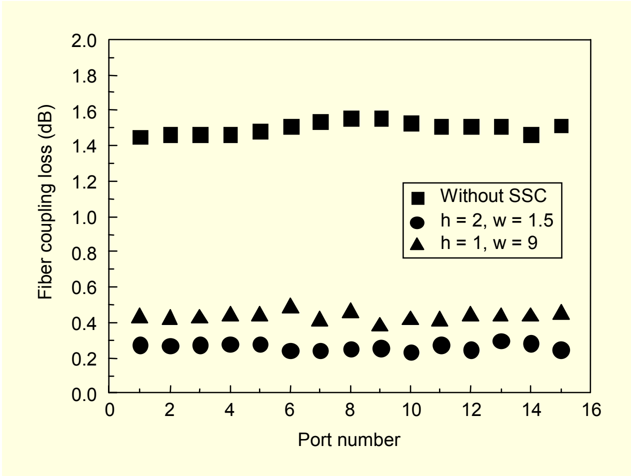

Fig. 6. Measured fiber-coupling loss of test waveguide circuits with and without the proposed SSC structure.

under proper etching conditions, the vertical taper is formed in the core layer (near the input/output waveguides) below the edge of the shadow-mask. No additional patterning process for the vertical tapered structure is required. The vertical-taper length is mainly determined by the spacing between the shadow-mask and the core layer. The taper length and the taper height were measured by a non-contact type interference microscope. The measured taper length with respect to the spacing is plotted in Fig. 5. For the spacing of 1.4 mm, the target taper length of 450 μm was achieved. It should be noted that the taper length cannot be made longer than 500 μm under our experimental conditions by increasing the height of the shadow mask. If we use the reactive-ion etching (RIE) system which has poorer anisotropic etching characteristics than the inductively-coupled plasma (ICP) etcher, then the longer taper length could be possible. Since the taper length that can be achieved by the shadow-mask etching technique is limited in either etching system, the taper design should be made as small as possible.

After forming the tapered core layer near the input/output waveguide region, patterns of optical waveguides are made using the conventional photolithography processes. The lateral tapered structure is formed in this step. Finally, the patterned waveguide core is enclosed by a silica overcladding layer.

For estimating the propagation loss and the fiber-coupling loss, we fabricated two types of straight test waveguides: the ones without the SSC and the others with the SSC. Except for the SSC, these two types of waveguides are identical, e.g., $\Delta = 1.5\%$ with its dimension of $4.5\,\mu\text{m} \times 4.5\,\mu\text{m}$. The length of the test waveguides was made different for estimating the propagation loss because the cut-back method which is generally used for estimating the propagation loss cannot be applied to the waveguides with the SSC. The measurement setup includes a 1550 nm laser diode, a photodetector, and a PDLmeter (polarization-dependent loss measurement equipment).

The propagation loss and the fiber-coupling loss in the case of the conventional waveguide without the SSC were measured to be 0.03 dB/cm and 1.52 dB, respectively. Hence, the propagation loss was very small compared to the fiber-coupling loss, which can be neglected in a practical sense.

The estimated fiber-coupling loss for test waveguides with the proposed SSCs is plotted in Fig. 6. The number of test waveguides is fifteen. Here, the fiber-coupling loss was calculated by subtracting the measured fiber-to-waveguide-to-fiber loss by the above propagation loss of 0.03 dB/cm. It also includes the taper-excess loss. The fiber-coupling losses were dramatically reduced from 1.52 dB to 0.28 dB with a cross-sectional dimension of $1.5\,\mu\text{m} \times 2\,\mu\text{m}$, and to 0.43 dB with its dimension of $9\,\mu\text{m} \times 1\,\mu\text{m}$. The PDL was measured to be less than 0.08 dB, implying that the proposed SSC structures do not affect the polarization characteristics.

We designed and fabricated a 40-channel 100 GHz AWG with the proposed SSC ($w = 1.5\,\mu\text{m}$, $h = 2\,\mu\text{m}$) incorporated in each region of the input/output waveguides. The basic waveguide structure has Δ=1.5% with its dimension of $4.5\,\mu\text{m} \times 4.5\,\mu\text{m}$ and a minimum bending radius of 2 mm. The path-length difference in the arrayed-waveguides and the free-spectral range were designed to be 25.51 μm and 8 THz, respectively. The free-spectral range was designed to be around two times wider than the actual demultiplexed wavelength range for improving the loss uniformity over the channels. The AWG chip dimension was 27 mm × 24 mm. The number of AWG chips on a 4-inch silicon wafer substrate were 12, which is three times larger than that of AWGs with the waveguide structure of $\Delta = 0.75\%$.

Figure 7 shows the measured transmission spectra. In measuring the AWG transmission spectra, we used commercially available equipment (JDSU SWS system). The wavelength resolution of this equipment is 3 pm. It can measure the polarization-dependent spectra as well. The insertion loss at the center channel was less than 2.8 dB with a loss-uniformity of 0.9 dB for all 40 channels, which was almost comparable to that of the AWG fabricated by the waveguide structure with Δ = 0.75% and the cross-sectional dimension of $6\,\mu m \times 6\,\mu m$. The PDL was less than 0.36 dB and the polarization-dependent wavelength shift was less than 0.02 nm. The 3 dB full-bandwidth was more than 0.4 nm and the channel crosstalk was less than −32 dB. This measured spectrum indicates that the proposed SSC structures improve the insertion loss without degrading other optical performance.

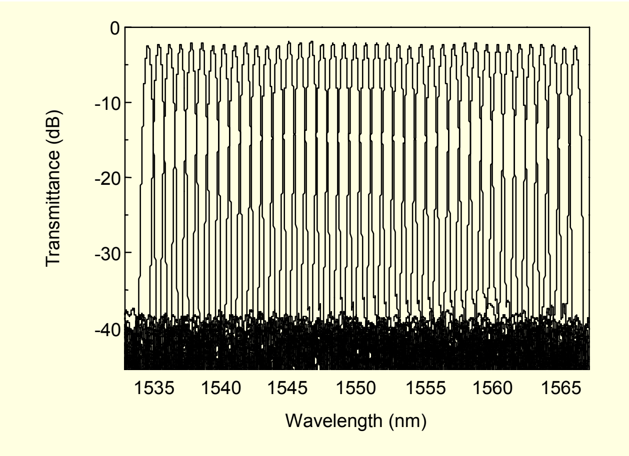

Fig. 7. Measured transmission spectra of the 40-channel 100 GHz AWG that incorporates the proposed SSC structures at the input/output waveguide regions.

IV. Conclusion

We have demonstrated a compact and low-loss 40-channel 100 GHz-spaced AWG with an SSC being incorporated at the input/output waveguide regions. The optimized SSC structures with a relatively short length of 450 μm were easily realized by the shadow-mask etching technique and improved the fiber-coupling efficiency by more than 1.1 dB at each coupling-point. The measured insertion loss of the AWG was 2.8 dB at the center channel without degrading other optical performance.

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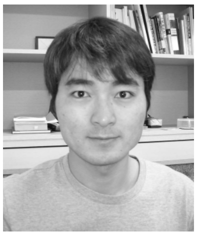

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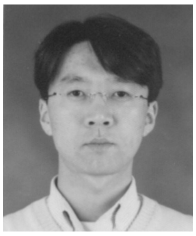

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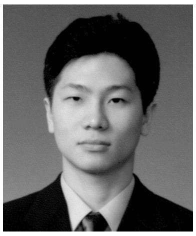

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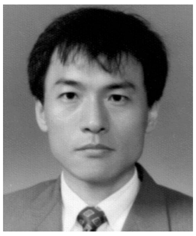

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