Development of Vertical Spot Size Converter (SSC) with Low Coupling Loss Using 2.5%Δ Silica-Based Planar Lightwave Circuit

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ABSTRACT Recently, new planar lightwave circuit (PLC) components are under study, in response to the requirement of downsizing and cost reduction, to increase their refractive index difference Δ between cladding and core. Accordingly, we are developing 2.5%Δ silica-based PLCs. However, it is difficult to put the 2.5%Δ silica-based PLCs directly into practical applications because their coupling loss with a single-mode fiber is as high as 2.9 dB/facet, raising a need for developing a spot size converter (SSC) to lower the loss. We have designed here, therefore, a new vertical SSC that has a broad core expanded in both horizontal and vertical directions, and fabricated the vertical SSC by combining plasma enhanced chemical vapor deposition (PECVD) and shadow mask. As a result, it has been confirmed that the use of the vertical SSC can significantly reduce the coupling loss between the 2.5%Δ waveguide and fiber to 0.06 dB/facet.

1. INTRODUCTION

Recently, as the optical networks becomes in widespread use accompanied by traffic increases, optical components in use are required to be smaller in size, lower in cost and lower in power consumption. In response to such requirements, studies on the silica-based planar lightwave circuit (PLC) components are going forward to increase the refractive index difference Δ between cladding and core to 1.5% or 2.0%[1), 2)]. It is known that, by increasing their Δ, PLC components can have smaller bending radius, and this leads to advantages such that optical components like arrayed waveguide grating (AWG) can be reduced in size, and simultaneously that their cost per chip can be reduced due to an increase in the number of chips per wafer. For example, whereas with Δ=0.8%, the bending radius is 5000 μm, it decreases to 800 μm when Δ is raised to 2.5%, and this results in a AWG chip downsized to about 15 mm square[3)]. Moreover, in the case of differential quadrature phase shift keying (DQPSK) decoder and the like that needs temperature control, downsizing results in a reduction in the area size to be temperature controlled, so that the necessary power consumption can be reduced.

However, an increase in Δ results in an increase in optical confinement effects, thereby decreasing mode field diameter (MFD), which in turn increases the mode field mismatch along with an increase in the coupling loss with fiber. For example, the coupling loss between waveguide and fiber is 0.5 dB/facet when Δ=0.8%, it rises to 2.9 dB/facet when Δ=2.5%, and this excessive coupling loss makes it difficult to directly use the waveguide as optical component. Because of this, it becomes necessary to have a spot size converter (SSC) to lower the coupling loss. Up to now, an SSC shown in Figure 1 has been reported, which expands the waveguide width using a horizontal taper[4)]. Use of this SSC can reduce the coupling loss to 0.25 dB/facet when Δ=0.8%, and to 1.5 dB/facet when=2.5%, but lower coupling loss is still needed for practical applications.

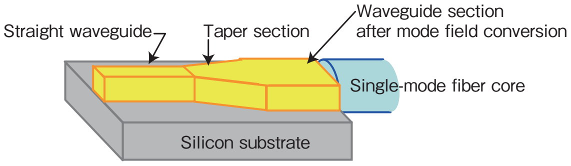

Figure 1 Structure of horizontal SSC.

Examples of SSCs with even reduced coupling loss include laterally narrow-tapered SSC[5)] and double-core laterally narrow-tapered SSC[6)] as shown in Figure 2. These SSCs have a narrow waveguide to make light leak out of the core in order to efficiently couple the light with a fiber, and achieve reduced coupling losses of 0.5 dB/facet and 0.2 dB/facet, respectively. But these SSCs have disadvantages in terms of fabricating processes in that, the narrow-tapered waveguide has to be strictly controlled for its distance between the taper and the end, and that the double-core laterally narrow-tapered waveguide has a very complicated fabricating process, in which cores having different Δ are grown twice and they are each formed into a waveguide shape.

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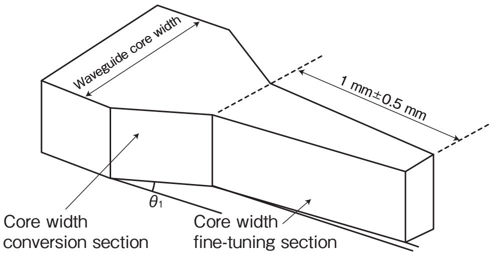
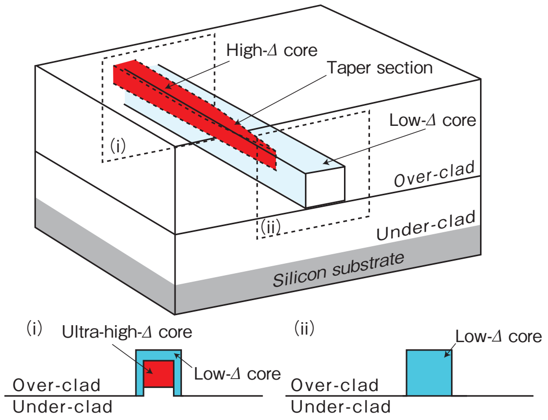
We have fabricated here, using a 2.5% Δ waveguide, a vertical SSC that has a facilitated fabrication process together with a reduced coupling loss with fiber. As a result, the coupling loss with fiber has been significantly reduced to 0.06 dB/facet. The details will be presented in this paper.



(a) Laterally narrow-tapered SSC.



(b) Double-core laterally narrow-tapered SSC.

Figure 2 Typical structures of SSCs studied.

2. DESIGN OF SSC

2.1 Structural Design of SSC

The SSC fabricated here has adopted a vertical structure in which the core is expanded in both the horizontal and vertical directions. The core size of a 2.5% Δ waveguide is normally 3.5 μm × 3.5 μm, which is smaller than that of a fiber. By expanding the waveguide core size, therefore, the MFD is expanded making the mode field mismatch smaller, to reduce the coupling loss with fiber.

Figure 3 shows the structure of SSC fabricated here, in which the core width of a 2.5% Δ waveguide is expanded first by a horizontal taper to form the first section shown in Figure 3, and then the height is expanded by a vertical taper to form the second section. Since the taper expands the core in the upper direction only and not in the lower direction down to the substrate, the waveguide has an asymmetric structure. Thus it is necessary to adopt separate processes to fabricate the horizontal and vertical tapers independently. In doing so, if the design is such that the core is expanded in the horizontal and vertical directions simultaneously, it is likely that the position of each taper shifts during the fabrication process with respect to the other, locally forming a core elongated in the vertical direction, and this can lead to loss of a specified shape. Accordingly, it was decided to expand the core in the horizontal and vertical directions at different positions, so as to mitigate the strict conditions of controlling the relative position of the two tapers, thereby making fabrication easier. The waveguide after core expansion in the horizontal and vertical directions, i.e., after mode conversion, is square in cross-section, being equal in the width and height. The width is indicated as “waveguide size” in Figure 3.

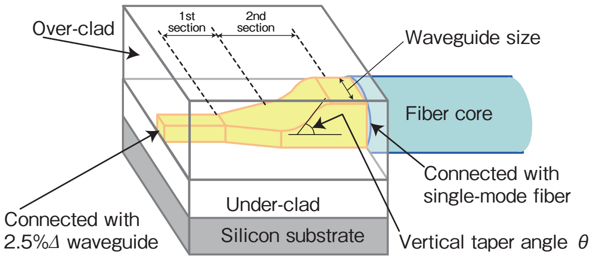


Figure 3 Structure of vertical SSC.

2.2 Design Parameters of SSC

To design the structure of a vertical SSC, it is necessary to have two parameters: waveguide size after mode field conversion, and taper angle in the vertical direction θ. The waveguide size after mode field conversion should be such that the coupling loss is minimized. And, the taper angle in the vertical direction θ should be such a value that is capable of mode field converting adiabatically without generating higher modes.

First, the waveguide size after mode conversion was determined. Simulations were run using the beam propagation method (BPM) to obtain light propagation conditions in the waveguide with changing waveguide widths for coupling with fiber, and the coupling loss with a fiber was calculated based on the optical electric field distribution after mode conversion. In this calculation, a square being equal in height and width was adopted for the waveguide shape after mode conversion. The calculated results are shown in Figure 4. While the coupling loss of a 3.5 μm-wide 2.5% Δ waveguide is normally 2.9 dB/facet, it decreases as the waveguide width is expanded because the MFD approaches that of fiber thus reducing the mode field mismatch. From Figure 4 it can be seen that the coupling loss reaches the minimum value of 0.06 dB/facet at a waveguide width of 12.5 μm. With larger waveguide widths, because the MFD becomes larger than that of fiber, the mode field mismatch rises again, increasing the coupling loss. Therefore, the waveguide width after mode conversion was determined as 12.5 μm, where the coupling loss with fiber reaches a minimum.

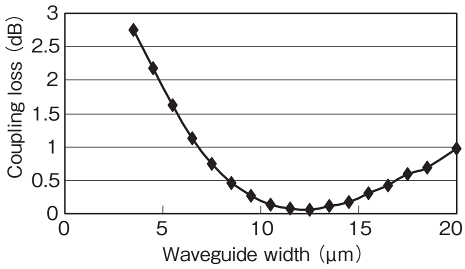
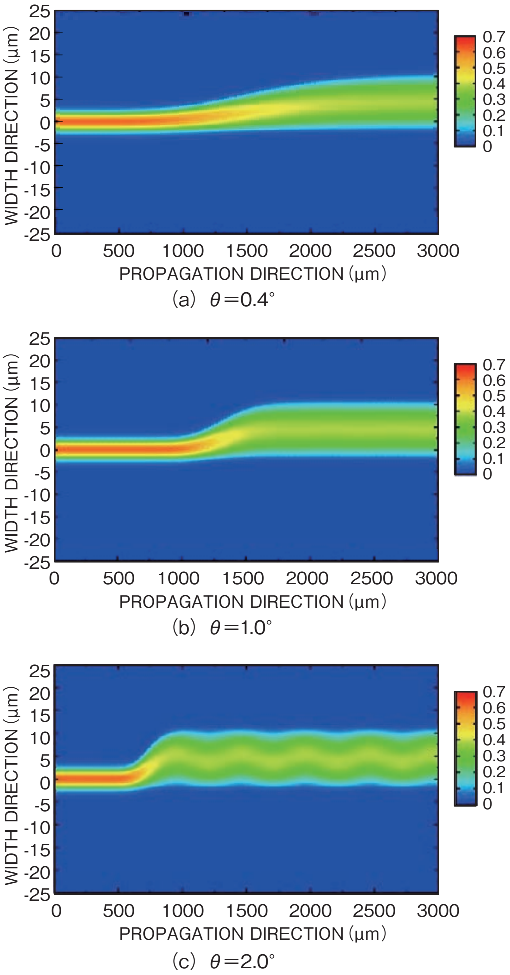


Figure 4 **Relationship between waveguide width and calculated coupling loss.**

Next, the taper angle θ for mode field conversion in the vertical direction was determined. Changes in light propagation conditions in the waveguide with changing taper angles were simulated using the BPM. The shape of waveguide structure was regarded to expand to the upper direction only, as shown in Figure 3. Figure 5 shows the simulation results of propagating conditions. It can be seen that, whereas adiabatical mode field conversion is achieved in the case of $\theta = 0.4°$ or $\theta = 1.0°$, higher modes are generated in the case of $\theta = 2.0°$.



(a) θ=0.4°

(b) θ=1.0°

(c) θ=2.0°

Figure 5 **Relationship between taper angle and simulated results of propagation.**

Subsequently, excess loss was calculated based on the simulation results, and the calculated results are shown in Figure 6. It is seen that, while the excess loss show virtually no change for $\theta < 1.0°$, it increases for $\theta > 1.0°$. Consequently, the requirement for the taper angle in the vertical direction is $\theta > 1.0°$. On the other hand, the smaller the tapering angle, the longer the taper length. Accordingly, it was decided to adopt $\theta = 0.6°$, taking both the chip size and process variations into consideration.

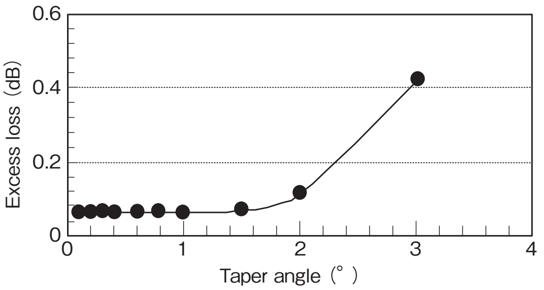


Figure 6 **Relationship between taper angle and calculated excess loss.**

3. DEVELOPMENT OF FABRICATION PROCESS FOR VERTICAL TAPER

A vertical SSC was fabricated on a silicon substrate, using PECVD and reactive ion etching (RIE). On this occasion, the taper in the vertical direction was fabricated, as illustrated in the process flow chart shown in Figure 7, in two steps using the PECVD and a shadow mask. First, the first core was deposited to have a height equivalent to that of normal waveguide. Next, the second core was deposited, using a combination of PECVD and shadow mask having a gap D from the substrate, to the height of waveguide after mode field conversion. If the gap D

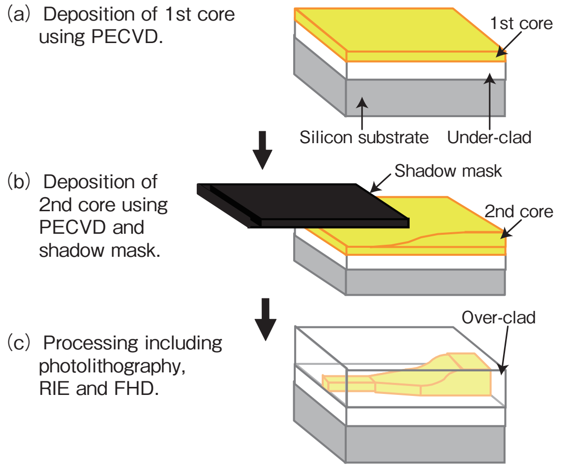


Figure 7 **Fabrication process of vertical SSC.**

between the shadow mask and the substrate is eliminated, deposition will not take place on the portion beneath the shadow mask so that the layer has a thickness of the first core, whereas the other portion has an increased thickness that includes the second core. But here, since a gap *D* was provided between the substrate and shadow mask as illustrated in Figure 8, the raw material gas flows into the gap during the PECVD process, thereby forming a gentle slope of layer at the end of the shadow mask [7]. This slope was utilized as the taper in the vertical direction. Subsequently, in the same manner as in the normal PLC fabrication process, a planar circuit pattern including the horizontal taper was formed, using photolithography and RIE, and finally, the core was embedded by depositing the over-clad using the flame hydrolysis deposition (FHD) method.

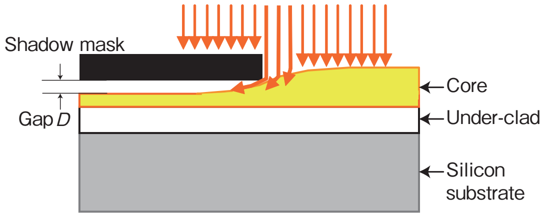
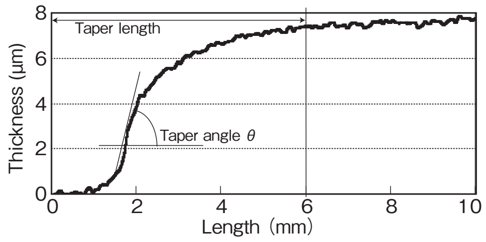
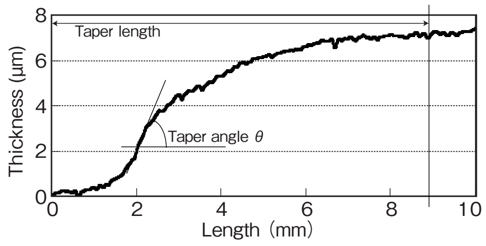


Figure 8 **PECVD process using shadow mask.**

Figure 9 shows the taper shapes changing with different gap *D* between the substrate and shadow mask during the deposition of the second core. The taper angle θ in Figure 9 is defined as the maximum slope of the taper. With *D*=0.6 mm, taper length and θ are 6 mm and 0.6°, respectively; and with *D*=1.2 mm, they are 9 mm and 0.3°, respectively. In other words, the wider the gap *D*, the smaller the taper angle, but the longer the taper length. On this occasion, since θ =0.6°, gap *D* was selected as 0.6 mm.



(a) *D*=0.6 mm



(b) *D*=1.2 mm

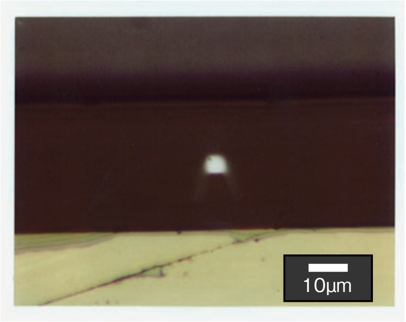
Figure 9 **Taper shape in the vertical cross-section.**

4. FABRICATION OF SSC

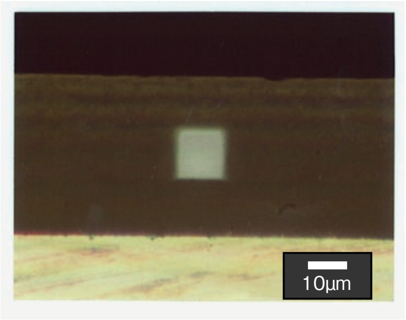
A vertical SSC was fabricated under the conditions determined so far. First, the vertical structure of a 2.5%Δ core was fabricated on a silicon substrate, using PECVD and shadow mask. Next, a vertical SSC was fabricated using photolithography and RIE, based on the positional relationship between the horizontal and vertical tapers as shown in Figure 3. Finally, the SSC core was embedded using FHD.

5. FABRICATION RESULTS

The vertical SSC fabricated here has, as shown in Figure 3, an endface of normal size to be coupled with a normal 2.5%Δ waveguide and another endface after mode conversion to be coupled with a fiber. These endface shapes were observed using an optical microscope, and the photos are shown in Figure 10. The sizes of these cores are 3.8 μm×3.5 μm and 12.8 μm×13.0 μm, respectively, substantially the same size as the design.



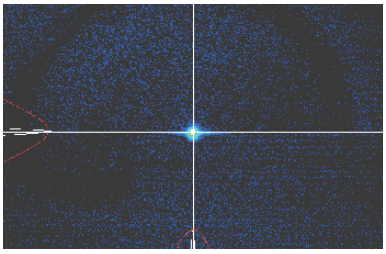
(a) Normal-sized core.



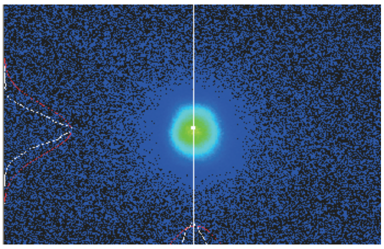
(b) Core after mode field conversion.

Figure 10 **Photos of vertical SSC cores on both ends.**

While inputting light from the normal-sized endface of a vertical SSC, the near field pattern of light emitted from another endface after mode field conversion was measured in order to confirm the spot size. In addition, for the sake of comparison, measurement was carried out using a normal 2.5%Δ waveguide to determine the light emitted from a normal-sized core. Figure 11 shows the measurement results of near field patterns. The photo on the top shows the measurement result of the light emitted from the normal-sized core, with an MFD of about 5 μm. And the bottom photo shows the measurement result of, while inputting the light from a normal-sized core, the light emitted from the core after mode field conversion by a vertical SSC, and the MFD is about 11 μm. From these measurements it has been demonstrated that the MFD has been converted from 5 μm to 11 μm, using the vertical SSC fabricated here. Moreover, from the fact that the circular shape is maintained unchanged, it is considered that mode field has been converted adiabatically in single mode.



(a) Normal-sized core



(b) Core after mode field conversion.

Figure 11 Measurement results of near field pattern of vertical SSC.

Figure 12 shows the measurement result of the near field pattern of light emitted from a single-mode fiber. The MFD is about 11 μm also, and the size and shape is the same as for the one converted by the SSC. From these results, it has been confirmed that the vertical SSC fabricated here has converted the MFD of normal-sized core to that of single-mode fiber.

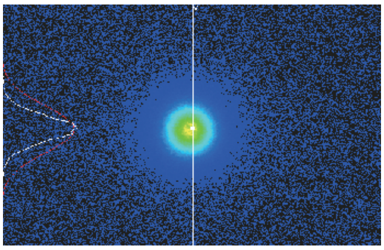


Figure 12 Near field pattern of SMF.

Subsequently, the coupling loss between the fabricated SSC and a fiber was determined. The insertion loss at 1550 nm of a waveguide chip having a vertical taper was measured first, then, the propagation loss of 2.5%Δ waveguide was subtracted to obtain the coupling loss with fiber. Figure 13 compares the measurement result with those of with a horizontal SSC and without SSCs. It is seen that the coupling loss is 2.9 dB/facet in the case of normal-sized core, and 1.5 dB/facet in the case of using a horizontal SSC. And, in the present case where a vertical SSC fabricated here is used, the coupling loss has been significantly reduced to 0.06 dB/facet.

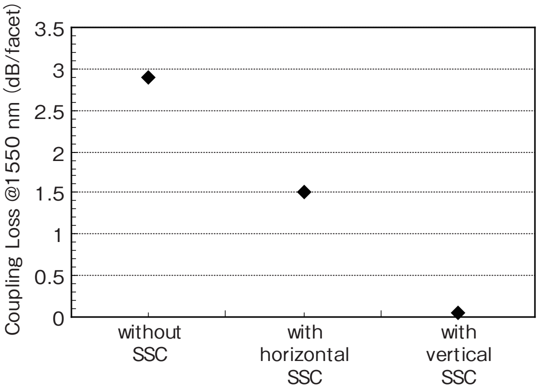


Figure 13 Coupling loss with SMF when SSC is used.

6. CONCLUSIONS

A novel structure of SSC was designed in which the core size was expanded to both horizontal and vertical directions.

By means of depositing using a combination of PECVD and shadow mask, a vertical SSC was fabricated using a 2.5%Δ waveguide.

It has been confirmed from the measured near field pattern of the fabricated SSC that the MFD of a 2.5%Δ waveguide has been converted to the MFD of a single-mode fiber. And by using the vertical SSC, the coupling loss between 2.5%Δ waveguide and fiber has been reduced to 0.06 dB/facet.

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