

Design of a Taper-Underlaid Spot-Size Converter with an Offset

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(Received March 5, 2007 : revised March 16, 2007)

We propose a taper-underlaid spot-size converter (TU-SSC) with an offset which consists of two vertically stacked taper layers. The designed TU-SSC reduces coupling loss of a high index-contrast waveguide with $1.5\% \Delta$ to a single mode fiber from 1.5 dB to 0.27 dB. We also considered the effects of mask misalignment in the fabrication process of TU-SSC, and optimized the design of TU-SSC so that the additional loss of TU-SSC for the mask misalignment of 3 μm in the photolithography process was as low as 0.13 dB.

OCIS codes : 230.7390, 250.5300, 130.0130

I. INTRODUCTION

Low loss coupling of a high index-contrast ($\Delta\%$) silica optical waveguide to an optical fiber is an important issue in current PLC (Planar Lightwave Circuit) technology since the increased integration of PLC functions needs sharper bending of optical waveguides [1]. The use of super-high-delta (SH Δ) optical waveguides (e.g. $1.5\% \Delta$) can reduce the bending radius of the waveguide to as small as 2 mm, so that more compact PLCs can be produced with negligible additional bending loss. However, there is a high coupling loss due to the mode mismatch when the fiber is butt-coupled to the high index-contrast waveguide. Therefore, an efficient spot-size converter (SSC) is needed to overcome the high coupling loss.

Recently, several SSC of silica and semiconductor based optical waveguides have been reported [2-7]. Mode expansion using a laterally reducing taper is relatively easy to achieve through a proper design of photo-masks [2-4], but it may suffer a high coupling loss due to mismatch in the vertical shapes of mode fields [2], tight tolerance on cutting position and narrow width of waveguides [3].

Mizuno *et al.* achieved low coupling loss of 0.3 dB to a standard single mode fiber for $1.5\% \Delta$ waveguide using a double tapered SSC structure. However, it showed relatively long length of 2-3 mm and tight margin of 0.2 mm in its cutting position [4] considering the cutting and polishing of the device.

On the other hand, the SSC with both a vertically

and laterally expanding taper showed lower coupling loss of 0.2 dB [5]. However, it uses a non-standard process like shadow-mask etching which may degrade the performance of precision devices such as AWG due to likely uneven etching of waveguide tops over the entire wafer.

A TU-SSC which is similar to the one which is proposed in this letter was originally introduced in the polymer based waveguide [6]. That work showed good coupling but required tight alignment of the mask.

It is well known that about 1 to 3 μm of photomask misalignment is common in the conventional photolithography process, and this leads to a difference between designed structure and fabricated structure. According to our 3-dimensional beam propagation method (3D-BPM) simulation, 3 μm of mask misalignment generates over 1dB of additional coupling loss. This unexpected degradation reduces the yield of PLC devices.

In this work, we designed a taper-underlay spot size converter (TU-SSC) with an offset, which has a good coupling efficiency with relatively short length and large tolerance in cutting position and photomask alignment in the fabrication process. Our 3D-BPM simulation shows that the TU-SSC with an offset reduces the coupling loss of $1.5\% \Delta$ high-silica waveguide from 1.5 dB to less than 0.3 dB with additional coupling loss of only 0.13 dB for the mask misalignment of 3 μm . The length of the TU-SSC with an offset is about 1 mm, and the tolerance of cutting position is larger than 300 μm .

II. DESIGN AND SIMULATION RESULTS

Fig. 1 shows the schematic structure of the conventional TU-SSC. TU-SSC consists of two vertically stacked layers of core, and each layer has a linearly increasing taper.

The index difference of the designed waveguide is $1.5\% \Delta$, and the width and height of the device waveguide are both $4 \mu\text{m}$ maintaining a single mode at 1550 nm wavelength. It is well known that the coupling loss between a single mode fiber and such a $1.5\% \Delta$ waveguide is about 1.5 dB/point .

We designed an up-tapered waveguide to increase spot-size horizontally together with an up-tapered lower layer located under the upper layer taper to increase spot-size vertically. In this way, the vertical expansion of core, which needs more complicated fabrication process in general, is not needed because the width of the lower layer taper is gradually increased so that the optical mode profile gradually moves into the lower layer taper. The basic TU-SSC design (Fig. 1 (a)) has $700 \mu\text{m}$ of taper length for both upper layer and lower layer, $11.5 \mu\text{m}$ of taper width, $4 \mu\text{m}$ of upper layer thickness and $7.5 \mu\text{m}$ of lower layer thickness. According to our 3D BPM simulation results, the coupling loss to a single mode fiber is 0.28 dB/point .

Fabricating a TU-SSC needs two photolithography processes for upper and lower tapered waveguides, which requires precise mask-alignment and a sharp edge for the lower taper. However, in a conventional photolithography process, mask misalignment of $3 \mu\text{m}$ is common in general. We simulated such a situation between the upper layer and the lower layer.

Fig. 1 (b) shows that the coupling loss increases from

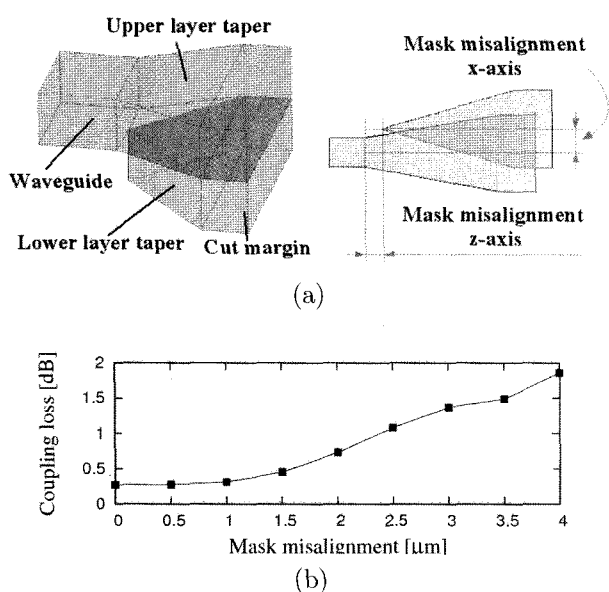


FIG. 1. (a) The structure and mask misalignment of the conventional TU-SSC, (b) Coupling loss of the conventional TU-SSC with mask misalignment between the upper and lower tapers

0.28 dB to 1.36 dB as the mask misalignment in x-axis increases from 0 to $3 \mu\text{m}$. For the case of the z-direction, a few microns of the mask misalignment is relatively small as compared to the length of taper, so that it rarely affects the coupling efficiency.

In our BPM simulations, the alignment position of a single mode fiber was adjusted to find a maximum coupling efficiency. These are similar to an active alignment technique in PLC packaging.

To reduce the mask alignment sensitivity, we modified the TU-SSC structure as in Fig. 2 (a). We introduced z-axis offset of the lower layer taper. The $3 \mu\text{m}$ of mask misalignment is a relatively large amount because the channel width of waveguide is only $4 \mu\text{m}$. Therefore, a tightly confined mode field is easily perturbed by the abrupt starting of the lower taper. On the other side, when an appropriate z-axis offset, i.e. $160 \mu\text{m}$ in this paper, is applied, such an effect of perturbation by the lower layer taper become smaller, because the mode field is expanded laterally during propagating through the offset of the upper taper. Therefore, the loss due to a radiative coupling in the TU-SSC becomes smaller. Slopes of the upper and the lower taper were kept almost the same because the differentiation of the slopes did not produce any significant effects. When the length of the taper was $750 \mu\text{m}$ for lower layer and $500 \mu\text{m}$ for upper layer, the coupling loss was then 0.27 dB . As the length of the taper was increased to as low as 0.15 dB which was identified as pure mode mismatch between the fiber and expanded waveguide core.

Fig. 2 (b) shows our 3D-BPM simulation results of the modified TU-SSC for the lower taper of $750 \mu\text{m}$. Without mask misalignment, the coupling loss is 0.27

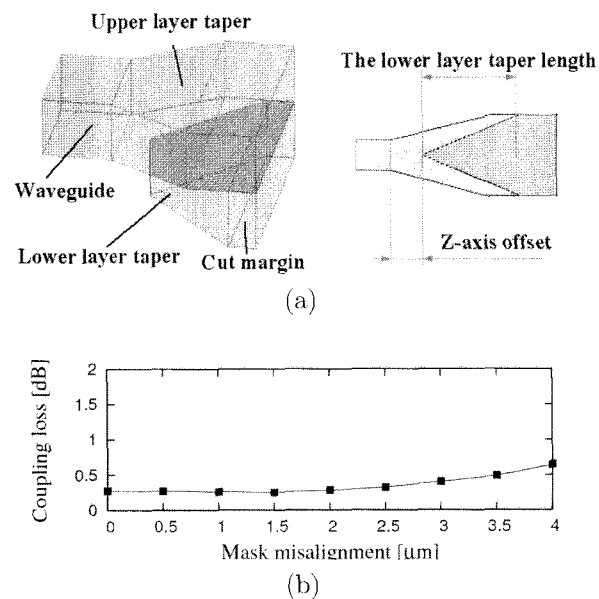


FIG. 2. (a) The Modified TU-SSC structure and z-axis offset, (b) Coupling loss of the modified TU-SSC with mask misalignment between the upper and lower tapers

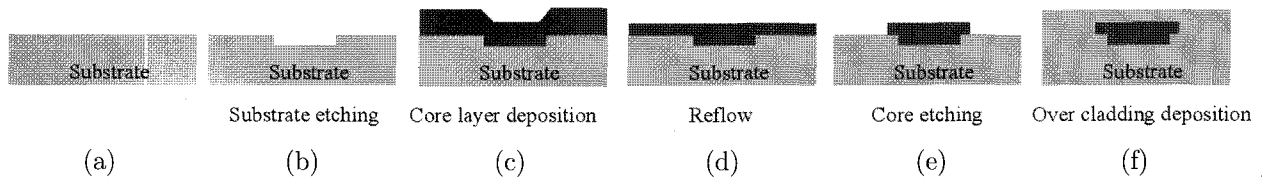
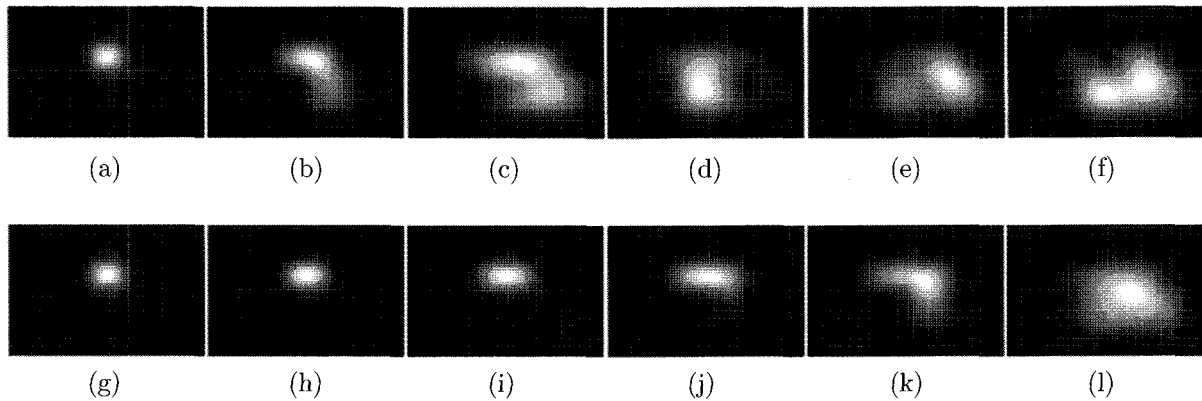


FIG. 3. Fabrication process of the TU-SSC

FIG. 4. Propagation field profile of the (a-f) TU-SSC, (g-l) modified TU-SSC with 3 μm of misalignment.

dB, and when there is 3 μm of misalignment, coupling loss is 0.4 dB. In comparison with the previous result of Fig. 1 (b), 0.96 dB of coupling loss was reduced when there is 3 μm of mask misalignment.

Fig. 3 shows the simulated cross-sectional mode field of the TU-SSC, misaligned by 3 μm without z-offset (from (a) to (f)), and the TU-SSC with z-offset (from (g) to (l)). When the mode field propagates through the TU-SSC (Fig. 1 (a)), it shares its confinement gradually with the lower layer of TU-SSC. Fig. 3 (a) shows the mode field of the 1.5% Δ waveguide. The tightly confined mode field moves into the lower layer taper (Fig. 3 (b)), and oscillates as the mode field propagates in the TU-SSC (Fig. 3 (c)-(f)).

On the contrary, if z-offset is 160 μm in the modified TU-SSC (Fig. 2 (a)), the mode field expands laterally while propagating the z-offset distance (Fig. 3 (g)-(i)), and is then perturbed by the lower taper (Fig. 3 (j)). Such a laterally expanded mode field is less sensitive to perturbation than a tightly confined mode field. Therefore, a suitable z-offset decreases efficiently the mask misalignment sensitivity.

An adiabatic transition was simulated for 2 mm, 3 mm, 5 mm, and 10 mm long tapers. Any non-adiabatic excitation to next higher mode produces oscillation behavior in its field through propagation. Increasing the taper length and z-offset improves such an oscillation. We confirmed that a taper longer than 3 mm reduces the oscillation in the fiber coupling to as low as 0.15 dB. However, 3 mm, that is, total 6 mm in length for input and output side, is relatively long considering the PLC device such as a splitter is only 10 mm long. Therefore the length of proposed TU-SSC

is set to be about 1 mm for a SH Δ PLC device in this letter which is not an adiabatic but an optimized structure. With such a TU-SSC structure, field oscillations exist during propagation and an output field profile of the TU-SSC may become different when the length of TU-SSC or input field mode profile changed. However, in most PLC device packaging, an active alignment technique is widely used. With such an active alignment method, the best alignment position of an optical fiber is not a fixed place, but a position that is flexible to the output mode profile. Therefore, in spite of the oscillation in the mode field of the TU-SSC, the coupling loss to an optical fiber is hardly changed.

In this work, the length of the upper taper and lower taper is optimized as 500 μm and 750 μm respectively, and the z-offset as 160 μm . The total length of the TU-SSC is about 1 mm and the cut-margin is over 300 μm . If the taper length becomes longer, the oscillation of mode field decreases, and the coupling efficiency increases further. The taper length and the coupling efficiency are in a trade-off condition. In this work, we set the length of TU-SSC to be less than 1 mm. If the length of TU-SSC is set to be longer, coupling efficiency and mode field oscillation can be improved further, which might be useful in some other applications.

Finally, a fabrication process for the TU-SSC is proposed as Fig. 4. Contrary to the conventional waveguide fabrication process, a trench for the lower layer taper has to be set before core layer deposition (Fig. 4 (b)). And then the core layer is deposited (Fig. 4 (c)). The total thickness of the core layer is defined as the summation of the lower layer taper thickness and the upper layer taper thickness. The top surface of the core

layer may have a slope because the substrate has some trench structure. To flatten the core surface, a core layer re-flowing method or a surface polishing technique can be used. If the core layer is deposited by flame hydrolysis deposition (FHD) methods, the core layer slope can be controlled up to a certain point during the annealing process in a furnace. After flattening of the core surface, conventional waveguide fabrication process, e.g. patterning, etching and over-cladding deposition, can be applied (Fig. 4 (e)-(f)).

III. CONCLUSION

In this work, we designed a taper underlaid spot size converter (TU-SSC), and optimized the TU-SSC's structure by modifying each taper length and the offset so that we reduced the TU-SSC's sensitivity to mask misalignment in the photolithography process. The coupling loss of the TU-SSC between the 1.5% Δ waveguide and a single mode fiber is 0.27 dB with no mask misalignment, and 0.4 dB with 3 μm of mask misalignment. Compared with a TU-SSC which is not modified, 0.96 dB of reduction of coupling loss is achieved with 3 μm of mask misalignment. The proposed TU-SSC design can be used in various PLC devices especially in high index contrast PLCs because it has a simple fabrication process, low loss with short length, high reliability such as mask alignment, and relatively large fabrication tolerance.

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