Low-Loss Spot-Size Transformer by Dual Tapered Waveguides (DTW-SST)

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Abstract—The insertion loss of a spot-size transformer by dual tapered waveguides (DTW-SST) is extremely reduced by controlling the shape of the tapered portion. This novel spot-size transformer is easily fabricated by using a shadow mask sputtering method. We describe a method to control independently the parameters of tapered portion such as maximum tapered angle, length, and position of tapered portion with respect to the edge of the shadow mask. A large transformation ratio (5 and 1/5) and a low insertion loss (0.7 dB) are successfully obtained.

I. INTRODUCTION

THERE HAS BEEN a serious but unrecognized problem of spot-size mismatching in integrated optics. Waveguide-type devices have various values of the spot size, ranging from about 0.2 μm for semiconductor lasers to about 4 μm for single-mode fibers. Therefore, when inserting integrated optic devices between semiconductor lasers and single-mode fibers, a waveguide-type spot-size transformer is necessary to reduce the coupling loss. Several spot-size transformers have been reported, using tapered waveguides, such as Ti:LiNbO₃ [1], a diffused waveguide in a glass substrate [2], and a plastic waveguide [3]. However, the transformable range is not wide enough (only several tens percent) because these were made of a uniform material and the refractive index of the core was slightly changed along the optical axis. To solve this problem, the authors proposed a dual tapered waveguide-type spot-size transformer [4], [5], made of the gradual overlapping of two tapered waveguides, and demonstrated a wide range transformation ratio (5 and 1/5).

In this paper, we describe a method to control the shape of tapered portion by a shadow mask sputtering technique and the simultaneous realization of both a low loss and a wide transformable range of spot size.

II. STRUCTURE AND DESIGN

When we consider a waveguide-type spot-size transformer using a tapered waveguide, we propose three possible structures, as shown in Fig. 1(a)–(c). Fig. 1(a) is made of uniform material and thus the index difference

Fig. 1. Spot-size transformer. (a) Tapered waveguide type. (Refractive index of core is constant.) (b) Tapered waveguide type. (Refractive index of core is gradually changed.) (c) Dual tapered waveguide type (this work).

between the core and the cladding is almost uniform along the optical axis. Fig. 1(b) is an ideal structure, in which the index difference changes gradually along the optical axis. Fig. 1(c) is the structure proposed by the authors [4], [5], in which two tapered cores having different core indices are overlapped gradually.

When we use Villuendas *et al.*'s definition [6] as the definition of the spot size w of three-layer symmetric slab waveguides,

$$w = \left[\frac{\int_{-\infty}^{\infty} \psi^2(x) dx}{\int_{-\infty}^{\infty} \left[\frac{d\psi(x)}{dx} \right]^2 dx} \right]^{1/2} \quad (1)$$

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the ratio of the spot size w and the core half-width a is expressed by

$$\frac{w}{a} = \left[\frac{V + \frac{1}{\sqrt{b}}}{V^3(1-b)} \right]^{1/2} \quad (2)$$

where V is the normalized frequency and b is the normalized propagation constant. Equation (1) is easily derived from Petermann's definition type II [7], which is widely used for optical fibers. Since the normalized propagation constant b is dependent on only the V parameter, (2) implies that the ratio of the spot size w to the core half-width a is expressed as a function of the V parameter. By using (2), we can easily calculate the relation between the spot size and the core half-width, which are normalized by the wavelength λ , as shown in Fig. 2. In Fig. 2 the refractive index of the cladding layer is assumed to be 1.4634 (SiO_2).

It is easily seen from Fig. 2 that when the relative index difference Δ is constant along the optical axis, as shown in Fig. 1(a), the spot size can hardly be transformed in a wide range by changing only the core half-width. Besides this, the spot size is larger when the core half-width is too small. Therefore we cannot expect a wide range transformation of the spot size by changing only the core half-width.

In the structure shown in Fig. 1(b), the refractive index and half-width of the core are changed simultaneously along the optical axis. In this case the insertion loss can be negligibly small as long as the tapered angle is small enough. If we can change the refractive index of core in a wide range, we can obtain a large transformation ratio of the spot size. Most of the conventional spot size transformers, such as tapered diffused waveguides and tapered plastic waveguides, are classified into this type. However, since these conventional types are made of a uniform material, the variable range of refractive index of core is not large enough. Therefore this type of spot-size transformer could not achieve a large transformation ratio of the spot size, only several tens percent at most. In addition to this, these conventional types, made by the diffusion process, are difficult to be fabricated on a semiconductor substrate and require a long tapered portion.

In previous reports [4], [5], we proposed a dual tapered waveguide-type spot-size transformer (DTW-SST), as shown in Fig. 1(c). Since the DTW-SST is constructed by the overlapping of two tapered waveguides which have different refractive indexes of core, the equivalent refractive index of core in the tapered portion can be regarded as changing gradually along the optical axis. Since the index differences of core in these waveguides can be designed independently, the DTW-SST can achieve a wide range transformation ratio of the spot size, as easily seen from Fig. 2.

We designed and fabricated the DTW-SST as shown in Fig. 3. In order to obtain a large transformation ratio of the spot size, the relative index difference of a thin-core

Fig. 2. Spot size against the core half-width in symmetric slab waveguides.

Fig. 3. Cross-sectional structure of dual tapered waveguide-type spot-size transformer (DTW-SST).

waveguide ($\Delta = 4.9$ percent) is designed to be much larger than that of a thick-core waveguide ($\Delta = 0.15$ percent). The key points of the design are as follows:

- 1) The V parameter of thin and thick core waveguides are set to be 1.4, a little smaller than $\pi/2$, to make the field profiles similar figures.
- 2) The tapered angles should be small ($< 1.0^\circ$) to reduce the insertion loss.
- 3) The length of the tapered portion should be short as long as the insertion loss is negligible.

The criterion of condition 2) is the propagation angle of the corresponding ray of the fundamental mode. The corresponding ray angles are calculated to be 11.4° for thin-core waveguide and 2.0° for thick-core waveguide (see Appendix II). Thus we designed the maximum tapered angle to be smaller than 1.0° .

III. FABRICATION

We fabricated the DTW-SST by an RF magnetron sputtering method. The thin-core waveguide was made of NA45 glass¹ core and SiO_2 cladding layers. In the thick-core waveguide, we realized a very small index difference ($\Delta = 0.15$ percent) between SiO_2 thick core and SiO_2 cladding layers by changing three conditions of RF sputtering, as shown in Table I. Taking into account the quality of formed film and the distribution of film thickness and refractive index, we determined the optimum conditions to produce the maximum refractive index difference. The distributions of film thickness and refractive index are shown in Fig. 4, together with these sputtering conditions. The film thickness is normalized by the film

¹NA45 glass is made by HOYA Corporation. The contents are almost the same as C7059 glass.

Fig. 4. Distribution of film thickness and refractive index formed by an RF magnetron sputtering apparatus.

TABLE I
SiO₂ SPUTTERING CONDITIONS

	Thick core	Cladding
Mixture ratio of oxygen and argon gases	Ar only	1:1
Applied RF power	0.3 kw	0.5 kw
Distance between substrate and target h	55 mm	50 mm

thickness at the substrate center, and h is the distance between substrate and target. The film thickness and the refractive index were measured by a prism coupler (PC-2000 made by Metricon Corporation). It is seen from this figure that the relative index difference Δ of 0.15 percent is obtained by using these sputtering conditions.

The tapered core was formed by using a shadow mask sputtering method, as shown in Fig. 5. First, a spacer made of Si chip was put on an Si substrate. Next, a metal shadow mask was put on the spacer so as to cover a half-part of the Si substrate. When a thin film is deposited on this substrate by an RF sputtering, a tapered portion is formed under the edge of the shadow mask. Let us define the parameters of the shadow mask, h_s , h_c , h_w , and h_t , as indicated in Fig. 5. In order to control the shape of the tapered portion, we investigated the change of the parameters of the tapered portion such as maximum tapered angle, tapered length, and relative position to the mask edge by changing the parameters of shadow mask h_s , h_c , and h_w .

First, we cut the corner edge of the shadow mask obliquely, as shown in the inset of Fig. 6, and compared the shape of tapered portions formed by using these shadow masks with and without the squared corner edge. The parameters of the shadow mask with a squared corner edge are $h_w = 600 \mu\text{m}$, $h_c = 0 \mu\text{m}$, and $h_s = 220 \mu\text{m}$ and those of the other shadow mask with the obliquely cut corner are $h_w = 200 \mu\text{m}$, $h_c = 400 \mu\text{m}$, and $h_s = 220 \mu\text{m}$.

Fig. 5. Principle of shadow mask sputtering.

Fig. 6. Maximum tapered angle and length of tapered portion against thickness of spacer.

Fig. 7(a) and (b) show the cross-sectional shape of tapered portions measured by a surface profiler. The length of the tapered portion and the maximum tapered angle evaluated from these figures are plotted in Fig. 6. We evaluated the length of tapered portion from the distance between two points having the thickness of 1 percent and 99 percent of flat part thickness. It is seen from these figures that we can remarkably reduce the maximum tapered angle to one-fourth that of the squared corner shadow mask (plotted by $\blacktriangle$ and $\triangle$) without enlarging the length of the tapered portion (plotted by $\bullet$ and $\circ$).

Next, the tapered portion was formed by changing the parameter h_s and the cross-sectional shape was measured by a surface profiler. Other parameters of the shadow mask sputtering such as h_c and h_w were kept constant. Fig. 6 shows the length of the tapered portion and the maximum tapered angle normalized by the film thickness against the thickness of spacer h_s . As h_s is thicker, the length of the tapered portion is longer and the maximum tapered angle is smaller.

Third, we formed the tapered portion by changing the height of wall h_w at the edge of the shadow mask and measured the position of the tapered portion against the edge of the shadow mask. Fig. 8 shows the length of the tapered portion formed outside the edge of the shadow mask and that inside the edge of the shadow mask against the height of the wall at the edge of the shadow mask. We

Fig. 7. Cross-sectional profile of the tapered portion measured by surface profiler. (a) With squared corner edge. (b) Without squared corner edge.

Fig. 8. Length of tapered portion outside and inside the edge of shadow mask against height of wall.

can see from this figure that when the height of the wall is higher, the length of the tapered portion outside the edge of shadow mask is longer, while the length inside the edge is almost kept constant. Thus we set the values of parameters as $h_w = 600 \mu\text{m}$, $h_c = 400 \mu\text{m}$, and $h_s = 220 \mu\text{m}$, when we fabricated the DTW-SST's.

Fig. 9 shows the fabrication process of the DTW-SST. All layers were formed by an RF magnetron sputtering method. We used a 3-in Si wafer as a substrate (Fig. 9(a)). In order to measure the insertion loss precisely by eliminating cladding modes, we introduced a NA45 glass antireflecting layer between the substrate and the cladding layer (b). Then, the SiO_2 cladding layer was formed successively by RF sputtering (c). Next, a thin NA45 glass core including tapered portion was formed by the shadow mask sputtering technique (d).

After the first taper was formed, we formed the second tapered portion so that the two tapered portions are

Fig. 9. Fabrication process of DTW-SST. (a) Si substrate. (b) AR layer (NA45). (c) Cladding layer (SiO_2). (d) Thin core (NA45). (e) Shadow mask contact. (f) Thick core (SiO_2). (g) Cladding layer (SiO_2).

Fig. 10. Positional relation between shadow mask and tapered portion.

overlapped thoroughly. However, since the tapered portion does not have symmetry, there are two center points to be overlapped. One is the position where the film thickness is half of the thickness at the uniform part, and the other is the center between the starting and ending points of the tapered portion. In this work, we fabricated the DTW-SST so that the former kind of center point overlapped with each other. The relative position of the overlapped tapers was controlled as follows: Fig. 10 shows the positional relation between the edge of the shadow mask and the formed taper when $h_w = 600 \mu\text{m}$, $h_c = 400 \mu\text{m}$, and $h_s = 220 \mu\text{m}$. The distance between the edge of the shadow mask and the center of the tapered portion with the half-thickness of the uniform part is about $50 \mu\text{m}$. Therefore, when the second shadow mask was adjusted to be parallel to the first one, we put a $100\text{-}\mu\text{m}$ -thick tape on the side wall as a spacer between these two shadow masks, as shown in Fig. 9(e). Then the initial shadow mask was removed and thick SiO_2 core was

Fig. 11. Measurement setup of insertion loss.

Fig. 12. Measurement setup of spot size.

Fig. 13. Measured result of far-field pattern.

formed to overlap with the tapered NA45 glass core precisely (f). Last, an SiO₂ cladding layer was formed after the shadow mask for SiO₂ core was removed (g).

The waveguide parameters of fabricated sample, such as the thickness of core and refractive indices of core and cladding, are the same as those shown in Fig. 3.

IV. MEASUREMENT

We measured the propagation loss of thin- and thick-core waveguides, the insertion loss of a spot-size transformer, and the spot size in both waveguides by a cutback method. Fig. 11 shows the measurement setup of the insertion loss. A He-Ne laser beam is focused on the input end of the waveguide by using a microscope objective lens. Output light is detected by a photodiode and measured by using a lock-in amplifier and a chopper.

When the spot size of three-layer symmetric waveguides is defined by (1), we can easily calculate the spot size from the measured far-field intensity profile by using

$$w = \left[\frac{\int_{-\infty}^{\infty} \Psi^2(\Omega) d\Omega}{\int_{-\infty}^{\infty} \Psi^2(\Omega) \Omega^2 d\Omega} \right]^{1/2} \quad (3)$$

Fig. 14. Loss versus waveguide length. (Light propagates from thick core to thin core. The waveguide parameters are the same as those shown in Fig. 3.)

Fig. 15. Spot size versus waveguide length. (Light propagates from thick core to thin core. The waveguide parameters are the same as those shown in Fig. 3.)

where Ψ^2 is the light intensity profile in the far-field pattern and Ω is the spatial frequency defined by $\Omega = k_0(x/z)$ (x is the distance in the transverse direction and z is the distance from the output end to the plane in which the FFP is observed). We measured the light intensity profile by using a p-i-n photodiode, as shown in Fig. 12. The measured result of far-field pattern is shown in Fig. 13.

V. EXPERIMENTAL RESULTS

Figs. 14 and 15 show the experimental results of the propagation loss and the spot size against the waveguide length when the light propagates from a thick waveguide to a thin waveguide. In Fig. 14, the slope corresponds to the propagation loss per unit length and the intercept corresponds to the coupling loss at the input end. The step between two straight lines shows that the insertion loss of the spot-size transformer is as small as 0.7 dB. It is seen from Fig. 15 that the spot size was certainly transformed from 2.7 μm to 0.5 μm (about 1/5 times). The theoretical values of spot size in Fig. 15 were calculated from (2).

Figs. 16 and 17 show the experimental results when the light propagates in the opposite direction. As shown in these figures, the insertion loss of the spot-size transformer is 1.0 dB and the spot size is widely transformed from 0.5 μm to 2.5 μm (5 times).

Two reasons can be considered for the discrepancy of insertion losses for different propagation directions. One is the measurement loss and the other is the difference of measured samples. Since we measured the insertion loss and the spot size simultaneously by a cutback method, it

Fig. 16. Loss versus waveguide length. (Light propagates from thin core to thick core. The waveguide parameters are the same as those shown in Fig. 3.)

Fig. 17. Spot size versus waveguide length. (Light propagates from thin core to thick core. The waveguide parameters are the same as those shown in Fig. 3.)

was impossible to measure the same sample in different directions. Although we used two samples cut from a same wafer, the distribution of thickness and refractive index might have caused the discrepancy of two measured insertion losses.

VI. SUMMARY

We have developed a controlling method of the shape of tapers by a shadow mask sputtering method and fabricated a new type of spot-size transformer DTW-SST, having a very smooth tapered angle and very precise overlapping of tapers. By using this technique, we successfully realized a low insertion loss (0.7 dB) and a large ratio of spot size transformation (5 and 1/5 times). The three-dimensional waveguide of the DTW-SST will not be so difficult by using a photolithographic technique.

APPENDIX I

COMPARISON OF DEFINITIONS OF SPOT SIZE IN THREE-LAYER SYMMETRIC SLAB WAVEGUIDES

Several definitions of spot size in optical fibers have been proposed, such as Petermann's definition type I [8], Anderson's definition [9], and Petermann's definition type II [7]. These definitions of spot size were originally introduced to approximate the splice loss of single-mode fibers by the coupling loss of Gaussian beams connected with an offset. It was clarified experimentally and theoretically that the splice loss could be estimated most accurately by Petermann's definition type II [10]. Therefore, Petermann's definition type II is popularly used for the definition of spot size for single-mode fibers.

In three-layer symmetric slab waveguides we can consider the following two definitions of spot size.

1) Villuendas's definition (w_v):

$$w_v = \left[\frac{\int_{-\infty}^{\infty} \psi^2(x) dx}{\int_{-\infty}^{\infty} \left[\frac{d\psi(x)}{dx} \right]^2 dx} \right]^{1/2} \quad (\text{A.II})$$

This equation is easily derived from the coordinate transformation of Petermann's definition type II.

2) $1/e$ width of the field profile (w_e):

$$\psi(w_e) = \frac{1}{e} \psi(0) \quad (\text{A.I2})$$

where $\psi(x)$ is the field profile. This is the simplest way to evaluate the spot size from the measured field profile when the field is close enough to Gaussian profile.

When two symmetric slab waveguides are spliced with an offset δ , as shown in Fig. 18, the splice loss α is expressed by

$$\alpha = -10 \log \frac{1}{(1 + V\sqrt{b})^2} \left[\frac{1-b}{\sqrt{b}} \exp\left(-\frac{V}{a} \delta \sqrt{b}\right) + \frac{3-2b}{2\sqrt{1-b}} \cdot \sin\left(\frac{V}{a} \delta \sqrt{1-b}\right) + \left\{ \sqrt{b} + \frac{V\left(2-\frac{\delta}{a}\right)}{2} \right\} \cdot \cos\left(\frac{V}{a} \delta \sqrt{1-b}\right) \right]^2 \text{ dB} \quad (\text{A.I3})$$

Since the spot sizes w_v and w_e normalized by core half-width a are expressed by

$$\frac{w_v}{a} = \left[\frac{V + \frac{1}{\sqrt{b}}}{V^3(1-b)} \right]^{1/2} \quad (\text{A.I4})$$

$$\frac{w_e}{a} = \begin{cases} 1 + \frac{1}{V\sqrt{b}} [1 + \ln \{\cos V\sqrt{1-b}\}], & (w_e > a) \\ \frac{1}{V\sqrt{1-b}} \cdot \cos^{-1} \frac{1}{e}, & (w_e \leq a) \end{cases} \quad (\text{A.I5})$$

the splice loss can be evaluated in terms of the offset normalized by the spot size as shown in Figs. 19 and 20. Figs. 19 and 20 show the relation between the splice loss and the normalized offset for the case of normalized fre-

Fig. 18. Butt joint of two slab waveguides having same spot size ($\psi(x)$ and $\psi'(x)$ are field profiles).

Fig. 19. Relation between splice (or connection) loss and normalized offset ($V = \pi/2$).

Fig. 20. Relation between splice (or connection) loss and normalized offset ($V = \pi/4$).

quency $V = \pi/2$ and $\pi/4$, respectively. When the field profile is exactly expressed by a Gaussian profile, the splice loss α is evaluated by [11]

$$\alpha = 4.34 \left(\frac{\delta}{w} \right)^2 \text{ dB.} \quad (\text{A.I6})$$

The splice loss calculated from (A.I6) is also shown in Figs. 19 and 20. Comparing the results obtained from (A.I1) and (A.I2) with the splice loss characteristics of Gaussian profile, it is clear that the splice loss in slab waveguides can be precisely approximated by that of the Gaussian profile by using (A.I1) as the definition of spot size.

APPENDIX II

CORRESPONDING RAY ANGLE OF FUNDAMENTAL MODE

The fundamental mode of three-layer slab waveguides can be regarded as the superposition of two plane waves propagating in two slightly different directions with the angle $\pm\theta$ against the optical axis (z axis). This angle θ corresponds to the ray angle, and the propagation constant

of mode is expressed by

$$\beta = k_0 n_1 \cos \theta. \quad (\text{A.III})$$

Using the definition of normalized propagation constant given by

$$b = \frac{(\beta/k_0)^2 - n_2^2}{n_1^2 - n_2^2} \quad (\text{A.II2})$$

the corresponding ray angle θ is expressed by

$$\theta = \sin^{-1} \sqrt{2\Delta(1-b)}. \quad (\text{A.II3})$$

Since the value of b is obtained from the V parameter through the dispersion relation, we can calculate the value of θ from given waveguide parameters, i.e., refractive indexes of core and cladding and the thickness of core.

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