Design of Tapered Rib Spot-Size Converter with Double-Cladding Structure[*]

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Abstract: A novel structure of spot-size converter is designed to allow low loss and large alignment tolerance between single-mode rib waveguide devices and fiber arrays theoretically. The spot-size converter consists of a tapered rib core region and a double-cladding region. Through optimizing parameters, an expanded mode field can be tightly confined in the inner cladding and thus radiation loss be reduced largely at the tapered region. The influence of refractive index and thickness of the inner cladding on coupling loss is analyzed in particular. A novel, easy method of fabricating tapered rib spot-size converter based on silicon-on-insulator material is proposed.

Key words: spot-size converter; tapered rib waveguide; coupling loss
PACC: 4280L
CLC number: TN432   **Document code**: A   **Article ID**: 0253-4177(2004)08-0913-05

1 Introduction

In order to facilitate the operation of alignment between rib optical waveguide devices based on the silicon-on-insulator (SOI) material and flat end fibers and make optical module packaging easy, fabricating V-grooves used to fix optical fibers and rib optical waveguide devices on the same SOI substrate is necessary. This method needs a large alignment tolerance between optical waveguide devices and fibers. However the tightly confined rib waveguides have a small (1~2μm), abnormal mode field, whereas standard single-mode fibers have a relatively large (8~9μm), circular one. This means that increasing alignment tolerance between them will particularly require spot-size converters (SSC) which convert the spot size of a propagating optical field and consequently provide low-loss and large alignment tolerance.

Although several kinds of spot-size converters have been reported[1-4], laterally and vertically tapered converters based on the SOI is seldom reported due to fabrication difficulty. Here, we propose a novel, easy method to obtain laterally and vertically tapered converters.

The SSC with a Si core and a SiO$_2$ cladding is bound to launch high-modes and therefore increase the propagation loss due to the large refractive index differentia between Si and SiO$_2$. This paper presents double-cladding structure of SSC, which is based on the SOI material. The relationship between structures of SSC and energy propagation loss is analyzed by using 3-D beam propagation method.

2 Design of SSC structures

The schematic structure of the SSC integrated with a single-mode rib waveguide is shown in Fig. 1. The rib width of the single-mode waveguide is designated as $3\mu m$ and the inner rib height is $5\mu m$. The outer regions of rib have a thickness of $3.2\mu m$. The section of the single-mode waveguide shapes trapezoid in anisotropic etching solution and the obliquity is $54.74°$. The tapered waveguide consists of a rib core region and a double cladding region, refractive indexes in the different regions are expressed as $n_{core}=3.5$, n_1, and $n_2=1.45(n_1>n_2)$, respectively. At one facet of the SSC, the width and height of the rib core are the same as those of the single-mode rib waveguide, and at the other facet, the width and height of the core are $6.2\mu m$ and $5\mu m$, respectively.
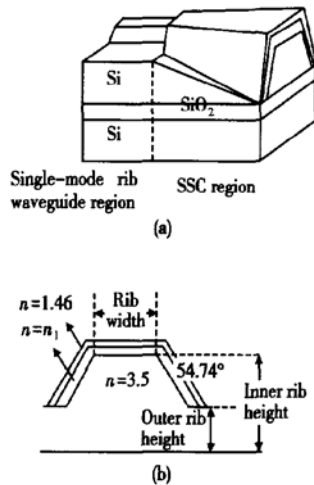

Fig. 1 Structure of the tapered rib SSC with double-cladding (a) Tridimensional figure of SSC; (b) Section view of SSC

The numerical simulation of SSC by 3-D BPM employed perfect match layer (PML) boundary condition and alternating direction implicit (ADI) method. The program was executed on Matlab platform. The default wavelength was set to $1.55\mu m$. The computation window was $16\mu m\times16\mu m$ plus $1.6\mu m\times1.6\mu m$ PML layer, and the computer step sizes in x, y, and z directions were 0.032, 0.032, and $1\mu m$, respectively. The input Gaussian field had a radius of $4\mu m$ representing optical field of the single mode fiber.

3 Results and discussion

When SSC structrues are designed for single-mode rib waveguides, the fiber-coupling characteristics of coupling loss and the degree of fiber-misalignment tolerance must be considered. The coupling characteristics are concerned with the expanded mode size and the shape that is determined by the sectional waveguide structures in the vicinity of the output facet. The optical field distributions simulated by BPM method at both facets of the tapered waveguide following by single-mode rib waveguide is shown in Fig. 2. After propagating $3000\mu m$ (including $1000\mu m$ of the tapered length), the input optical field with a Gaussain shape converts into the another different shape
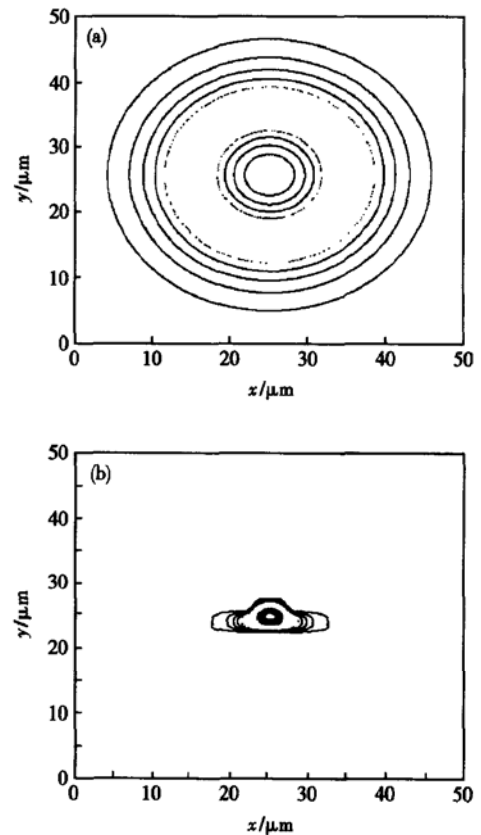

Fig. 2 Optical field distributions at the both facets of the SSC (a) Input; (b) Output

which is the single-mode rib waveguide optical field's match.

Another important function of the SSC is to increase fiber-misalignment tolerance, which is shown by Fig. 3. Refractive index of the inner cladding is 3.34, which equates that of GaAs, and the thickness is 1μm. The horizontal and vertical alignment is less sensitive with the SSC because of the change in the numerical aperture.
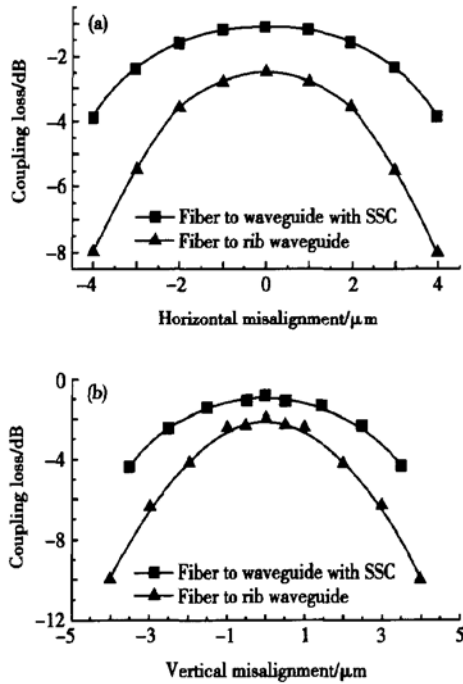

Fig. 3 Calculated coupling loss of a single fiber-SSC interface from misalignment in the horizontal (x) and vertical (y) directions compared with the fiber-rib misalignment coupling loss

It is not an adiabatic propagation in the tapered waveguide because of radiation loss brought by high-order modes, however, the loss can be reduced by decreasing the sloping angle or increasing the length of tapered waveguide. Unfortunately, the radiation loss is reduced by the above method at the expense of increasing size of chip. Therfore the length of SSC generally is in the range of 100 and 500 μm. In order to save compute time the length of SSC is 100μm in this paper, whose sloping angle (0.03°) is small enough to reduce radiative loss. The coupling loss is obtained by overlap integral of optical field distributions between SSC and single-mode rib waveguide.

In order to analyze the influence of inner cladding refractive index on the propagation power in the core region, we change the refractive index (n_1) of the inner cladding from 1.95 to 3.45, and the step is 0.5. The thickness of inner cladding region in these waveguides equates 0.5μm. Figure 4 shows comparison of the propagation powers in the core regions normalized by input power. Curve a and b in Fig. 4 represent the propagation powers of the single-mode rib waveguide and the SSC with SiO₂ mono-cladding, respectively. Obviously, there is a higher propagation power in the tapered waveguide than that in the single-mode rib waveguide. Moreover, the attenuation of optical energy in the tapered waveguide greatly decreases.
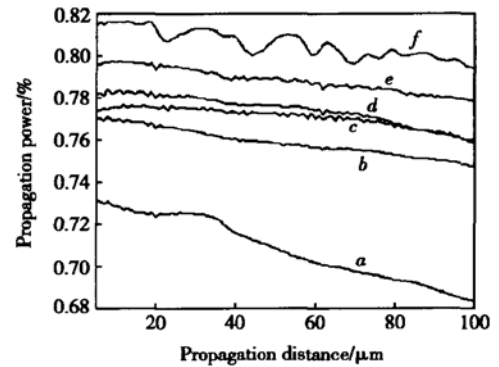

Fig. 4 Propagation power as a function of refractive index of the inner cladding

Curves c, d, e, and f in Fig. 4 describe the propagation powers of the tapered waveguides with double-cladding and the refractive indexes of their inner cladding are 1.95, 2.45, 2.95, and 3.45, respectively. A regulation that the propagation power increases along with a decrease of the refractive index differentia between the core region and the cladding region is shown by these figures. It can be explained by the following formula,

$$V = \frac{2\pi}{\lambda}\rho_{\text{eff}} \sqrt{n_{\text{core}}^2 - n_1^2}$$

where V represents unitary work frequency and ρ_{eff} represents the effective size of a tapered rib waveg-

uide. Under the condition of keeping ρ_{eff} constant, the larger refractive index differentia between the core region and the cladding region, the more high-order modes will be launched in a tapered waveguide due to large V. High-order modes will be partly radiated from single-mode waveguide and consquently lead to energy loss.

In addition, when the refractive index differentia is less than 0.05, oscillation of the energy curve becomes obvious. It is because that a tapered waveguide with a small refractive index differentia between the core region and the cladding region has a small numerical aperture, which results in more optical energy leaking out from the core region and then being confined in the inner cladding region. The optical fields coulping between the both regions will become obvious, that is, a part of energy repetitively transform from one to another during propagating. Considering the fact that the energical oscillation will decrease the signal-to-noise ratio of the optical waveguide devices, we should select these materials whose refractive index ranging between 2.0 and 3.45 used as inner cladding of the SSC. Therefor, N-doped SiO₂, LiNbO₃, and GaAs should be adopted.
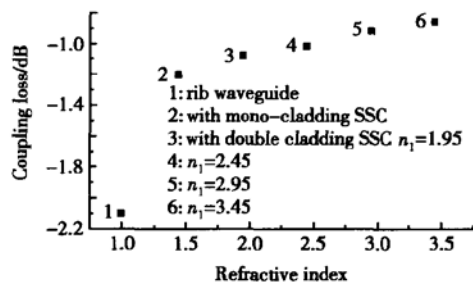
Fig. 5 Coupling loss in the different structures

Figure 5 represents the coupling losses in rib waveguides with different convertors. There is the same regulation as shown in Fig. 4.

The thickness of the inner cladding must affect the coupling efficiency according to the coupling effect. When the refractive index of inner cladding maintains the value of 2.95 invariable, the thickness of inner cladding region changes from 0.05 to 2.0μm. Fig. 6 shows the coupling losses corresponding to the different thickness.

Dots a, b, c, d, and e in Fig. 6 represent the coupling loss of the thickness of 0.05, 0.1, 0.5, 1.0 and 2.0μm, respectively. When the thickness less than 0.5μm, the increasing of thickness would enhance the ability to confine optical field and then reduce coupling loss. Whereas when the thickness larger than 0.5μm there is a decrease in coupling efficiency, because the energy in inner cladding that could not couple into the core region will radiate away at the joint of SSC and single-mode rib waveguide.
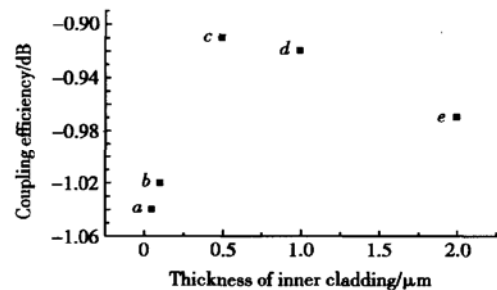
Fig. 6 Coupling loss as a function of the thickness of inner cladding

4 Fabrication method

The technological processes of fabricating vertically tapered SSC involved complicated growth techniques, like shadow mask growth or selective growth[5], or diffusion limited etching and precisely controlled polish. In previous techniques, growth techniques are more applicable for compounds than for silicon and the later two techniques are not only difficult but also costly. This paper presents a novel, easy technique for fabricating vertically tapered waveguides, and the experimental setup is shown in Fig. 7. A prepared SOI wafer hanged on the step motor whose single step is within micron magnitude is gradually immersed into KOH solution under the precisely control of a computer. The fore-and-aft parts of the SOI wafer undergo different etching time in the KOH solution and thus vertical-
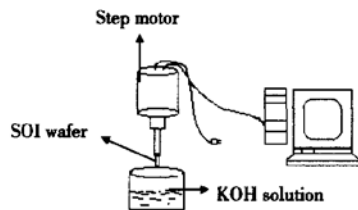
ly tapered SSC is shaped.

Fig. 7　Experimental setup for fabricating tapered rib SSC

5　Conclusion

Structures of SSC for low-loss coupling and large alignment tolerance between a single-mode rib waveguide and a fiber are designed theoretically in this paper. The SSC consists of a tapered rib core region and a double cladding region, which tightly confines the expanded mode field and reduces radiation loss at the tapered waveguide. Through the above analysis, the inner cladding materials such as N-doped SiO_2, $LiNbO_3$, and GaAs, whose refractive index ranging between 2.0 and 3.45, can be used for the SSC. The optimized thickness of inner cladding is about $0.5\mu m$. The calcu-lated coupling efficiency can be increased by 20% compared with that of rib waveguide. In addition, the paper proposes a novel, easy method of fabricating tapered rib SSC based on silicon-on-insulator material.

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有双包层结构的楔变脊型光斑转换器的设计*

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摘要: 为了提高硅基上单模波导器件与单模光纤的耦合效率和工艺容差, 设计了一种实用新型光斑转换器, 它由水平和垂直双向楔变的波导芯区和双内包层构成. 分析了内包层折射率与其厚度对耦合效率的影响, 发现通过优化内包层的参数可以加强对扩展光场的限制. 针对在硅基上制作垂直楔变结构的波导还很困难的情况, 提出了一种低成本、简单可行的制作方法.

关键词: 光斑转换器; 脊型楔变波导; 耦合损耗

PACC: 4280L

中图分类号: TN432　　　**文献标识码:** A　　　**文章编号:** 0253-4177(2004) 08-0913-05