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https://doi.org/10.15017/1906119

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 3, pp.19-20, 2017-10-19. Interdisciplinary Graduate School of Engineering Sciences, Kyushu University
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Realization of a Stacked Waveguide using Higher Refractive Index Material with SiO_2 as Cladding

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Abstract: *A vertically coupled directional coupler device using a three-dimensional (3D) structure is proposed. The structure consists of two stacked waveguides with the high refractive indexed material ZnO as core and SiO_2 for the clad material. The power coupling between the two waveguides occurs only in the vertical direction. The presented device was simulated by a 3D beam propagation method (BPM) to investigate the light propagation and to measure the reflectance. In order to implement the real structure, the fabrication tolerance should be considered. Here, the fabrication tolerance of the designed device is discussed thoroughly as well as the fabrication process is discussed. As a result, fabrication tolerance of ±25% in the device length and ±20nm in the core thickness of the waveguide were achieved successfully.*

Keywords: Stacked waveguide, Vertical coupling, Fabrication tolerance

1. INTRODUCTION

Continuous development in integration of optics and electronics has made the optical communication systems more compact in size and highly effective in usage. Instead of bulk-type structures, various waveguide types optical devices (isolators, modulators, directional couplers) have been commonly used and widely studied by many researchers [1-2]. At present, there has been a prominent interest in devices that incorporate three-dimensional (3D) structures. Because 3D structures facilitate integration of bulk shape into minute and are useful for sensor and telecommunication applications [3-4]. Moreover, optical losses and cross-talk can be reduced by growing structures in vertical direction. It is noteworthy to mention that 3D devices can be shorter than conventional planar type devices and light is shifted into these devices by coupling lower and upper waveguides.

In this work, we simulate and analyze a basic 3D structure by comprising two planar directional coupled waveguides where the cores are stacked in vertical direction. The two cores are stacked in close proximity, therefore allows to exchange power in vertical direction depending on the coupling length (Fig.1). Spin-coating will be used to produce different layers that will stack one on another. Waveguide shapes will be created by a masking technique based on UV photolithography. Here, the well-known conventional planar technology will be used to make layers and to create waveguide shapes; however, the key challenge is to form and align two waveguides perfectly in the vertical direction.

In this paper, first the theory and modelling of the stacked waveguides are described briefly. Then the fabrication tolerance will be explained thoroughly followed by simulation results and discussion.

2. THEORY AND MODELLING

Stacked waveguide as shown in Fig.1 is designed for the operation of fundamental mode propagation at 1550nm wavelength. For analysis and simulation purposes, 3D beam propagation method (BPM) was employed in order to determine the field distributions and effective refractive index of the structure. Electric field profile and mode profile with effective refractive index of the designed structure are shown in Fig.2. The waveguides are of cross-section (2 x 0.3 μm^2) where width = 2μm and thickness = 0.3μm with a 1.5μm spacing between two waveguides. For cladding and spacing material SiO_2 is used and the refractive index of SiO_2 is 1.444 at 1.55μm wavelength. ZnO is incorporated as core material and the core refractive index (1.9267) is around 33% higher than clad. Light is launched into the lower waveguide, then coupled and comes out with the upper waveguide. The result of the numerical modelling is shown in Fig.3. It can be derived from that figure, the guided power transfers between the lower waveguide and the upper waveguide repeatedly which is situated exactly on top of lower waveguide with a spacing between these waveguides.

In most of the conventional analyses of the directional couplers, butt coupling coefficient and change in propagation constant (δ) were neglected and assumed to be zero. However, the mode-coupling coefficient or simply coupling coefficient (κ) is very important for the calculation of the coupling length.

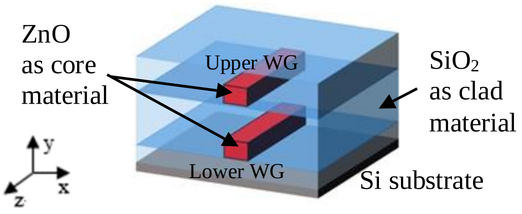

Fig. 1. 3D structure of stacked waveguides

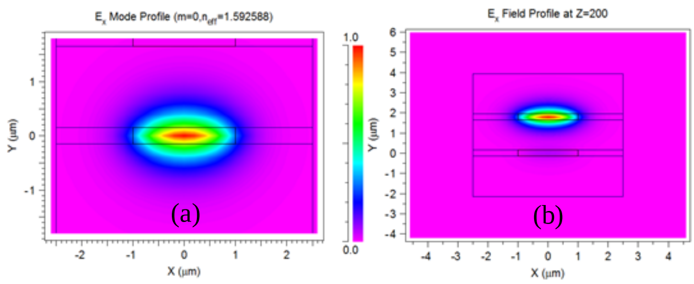

Fig. 2. (a) Effective refractive index, and (b) Electric field distribution of 3D structure

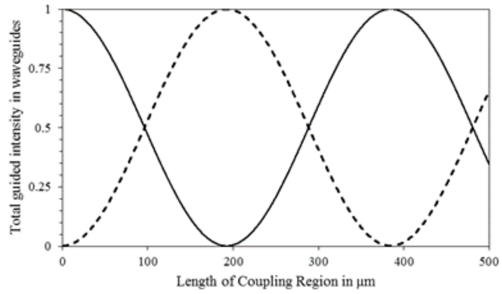

Fig. 3. Total guided power in the waveguides of 3D structure vs. length of the coupling region with i/p in lower WG only. Light propagation through lower WG (Solid line) and upper WG (Dashed line)

We can derive an analytic solution for the coupling coefficient by means of the Coupled Mode Theory [5]. If z is the coordinate in propagation direction, then the optical power flows into the waveguides along z-direction is given by

$$P_{lower}(z) = 1 - \left(\frac{\kappa}{q}\right)^2 \sin^2(qz)$$

$$P_{upper}(z) = \left(\frac{\kappa}{q}\right)^2 \sin^2(qz), \text{ Where } q = \sqrt{\kappa^2 + \delta^2}$$

The power coupling efficiency from excited lower waveguide to upper waveguide reached maximum at

$$z = \frac{\pi}{2q}(2m+1)$$

The length z at $m=0$ is coupling length, L_c and with $\delta=0$

$$L_c = \frac{\pi}{2\kappa} \qquad \text{(Eq.1)}$$

The coupling coefficient of the directional coupler consisting of two waveguides is given as

$$\kappa = \frac{\sqrt{2\Delta}}{a}\frac{u^2 w^2}{(1+w)v^3}\exp\left[-\frac{w}{a}(D-2a)\right] \qquad \text{(Eq.2)}$$

Where, a = half width of waveguides; D = distance between center of two cores; u, v, w = normalized transverse wavenumbers; Δ = refractive index difference between core and clad.

3. FABRICATION TOLERANCE ANALYSIS

In order to realize the fabrication of a 3D stacked waveguides, the fabrication tolerance should be considered. In the practical fabrication, it is quite impossible to control exactly the waveguide dimensions. A small change in the parameter including waveguide width, thickness, spacing between both waveguides, and length in coupling region would causes a certain change in the device performance. From Fig. 4 (a), it is clearly seen that change in the width of waveguides has less impact on power coupling unless there is a reduction of width. For 35% less than the designed width (2µm), more than 80% power is shifted from lower to upper waveguide. A change of ±25% in

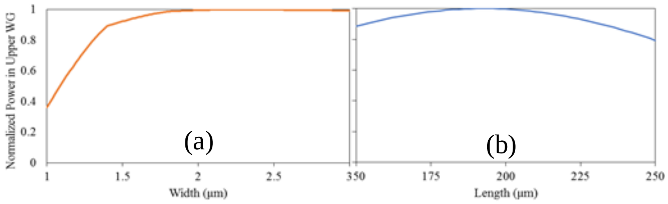

Fig. 4. Change in (a) width, and (b) coupling length

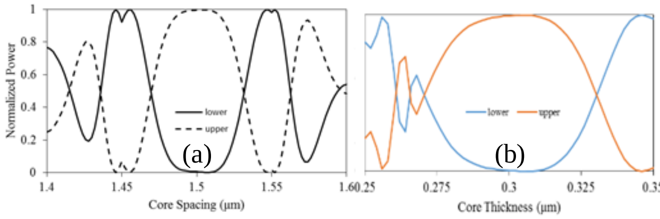

Fig. 5. Change in (a) core spacing, and (b) thickness

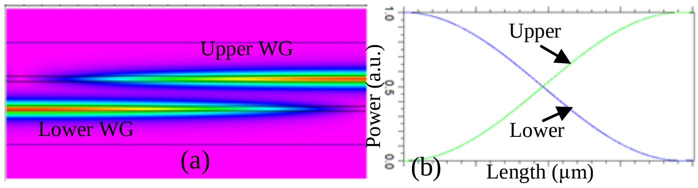

Fig. 6. (a) Light propagation, and (b) power transfer into waveguides

the length will allow more than 80% power transfer between these waveguides (Fig. 4b). However, a small change in the spacing distance has large impact on coupling, shown in Fig. 5(a). For our designed structure, a spacing distance equal to 1.5µm ± 30nm is acceptable i.e. 30nm change in coupling length permit more than 80% light propagation into upper waveguide. In case of waveguide thickness, this structure can tolerate 20nm change in order to get more than 80% coupling between lower and upper waveguides (Fig.5b).

4. SIMULATION RESULTS AND DISCUSSION

After rigorous arithmetic solution and by utilizing Eq.2, values for κ of designed 3D structure was calculated 8.73 mm^{-1} which in turn gives L_c = 180µm (using Eq.1). The simulation result is shown in Fig.6 and found coupling length equal to 192.3µm which is close to the calculated value.

5. CONCLUSION

A 3D structured device where coupling occurs in vertical direction has been analyzed and realized by BPM. We have discussed the fabrication tolerance for the designed structure based on the simulation results, and successfully obtained ±25% and 20nm tolerance in the device length and core thickness respectively. It is possible to fabricate the real structure by employing a simple spin coating and photolithography technique.

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