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High Efficient Unidirectional Optical Coupler for Through Silicon Photonic Via in Optoelectronic 3D-LSI

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1. Introduction

As scaling-down the device size, signal propagation delay and interconnect power dissipation have increasingly become critical problems for realizing a high performance LSI. To overcome these problems, 3D-LSI has attracted much attention [1]. On the other hand, on-chip optical interconnection is also promising candidate due to the many advantages such as high speed, high density, less crosstalk, and high tolerance to EMI (electromagnetic interference) [2]. In order to realize the high performance computing system, we have proposed optoelectronic 3D-LSI as shown in Fig. 1 [3]. On-chip optical interconnection in the 3-D LSI allows higher speed and wider bandwidth communication between local blocks separately placed on each LSI chip. The optical interconnection also provides the input-output data transfer with the high-speed and wide-bandwidth for each LSI chip. The optoelectronic 3D-LSI will achieve the high performance computation using massively parallel operation with the 3D stacked structure and optical interconnection.

For the optoelectronic 3D-LSI, through Si photonic vias (TSPVs) is proposed to form optical interconnection for light propagation to/from each stacked LSI chips [3]. Optical couplers are required to optically connect the TSPV and a planar optical waveguide on the stacked LSI chips, as shown in Fig. 2. In this paper, we propose high efficient unidirectional optical coupler between the TSPV and planar optical waveguide and evaluate its coupling efficiency by using FDTD (Finite-Difference Time-Domain method) simulation.

2. Proposal of Unidirectional Optical Coupler

To couple the TSPV with planar optical waveguide, bending the direction of light propagation by 90 degrees is required. 45-degree mirrors are well known to be an optical device which can satisfy such requirement. However, there is large size mismatch between the TSPV and the planar optical waveguide. Typical size of the TSPV and the planar optical waveguide are 5.0 x 5.0 μm^2 and 0.3 x 0.3 μm^2, respectively. Therefore, the 45-degree mirrors will result in a low optical coupling efficiency. Grating couplers are reported as another optical device to make 90 degree bend in the light propagation direction [4-6]. The grating couplers can overcome the size mismatch problem described above. However, optical losses induced by zero order light and light propagation in unwanted direction are big concerns. Therefore, we propose a novel high efficient unidirectional optical coupler to overcome these problems. As shown in Fig.3, the unidirectional optical coupler is the grating coupler with two reflective mirrors to efficiently guide light in the intentional direction. One is mirror A located above TSPV, and the other is mirror B flanked in the unwanted direction. A grating coupler with only the mirror A to reduce the optical loss caused by zero order light was proposed by Yamada *et al.* [4]. Our unidirectional optical coupler has not only the mirror A but also the mirror B to reduce light transferred in unwanted direction.

3. Simulation of Unidirectional optical coupler

We evaluated the unidirectional optical coupler by FDTD simulation. TE polarized light with a wavelength of 1.55 μm was used as incident light. Ag was employed for the mirror material due to the low-loss property for the wavelength. A core material of planar optical waveguide was Si and a background cladding material was SiO_2. A thickness of the planar optical waveguide and pitch of the grating was kept constant at 0.2μm and 0.54μm, respectively. The position of the two mirrors was defined by D_A and D_B as depicted in Fig. 3.

A coupling efficiency with varying D_A was shown in Fig. 4. In this simulation, no mirror B was used to remove the effect. In the case of D_A with 0.54 μm, the reflected light satisfies the requirement described by the following equation related to the conditions for constructive interference:

$$D_A = \frac{1}{4}\frac{\lambda}{n_{SiO_2}}(2k-1) \qquad (1)$$

where λ is a wavelength, n_{SiO_2} is a refractive index of SiO_2 (~ 1.44), and k is a positive integer. This light is reflected in backward direction. Hence, to realize high coupling efficiency, we have to design the unidirectional optical coupler so as not to satisfy the above equation (1). The coupling efficiency with varying grating height was shown in Fig. 5. The highest coupling efficiency was achieved when grating height was 40 nm. The coupling efficiency with varying D_B was shown in Fig. 6. For D_B of 0.216 μm and 0.486 μm, the constructive interference conditions for the reflected light are described by the following equation:

$$D_B = \frac{1}{2}\frac{\lambda}{n_{eff}}k \qquad (2)$$

where n_{eff} is a effective refractive index. In this case, the reflected light with the constructive interference conditions was transferred in our intentional direction, leading to very high coupling efficiency.

As a result of the design optimization, this unidirectional optical coupler can achieve almost 80% coupling efficiency. We compared the unidirectional optical coupler with conventional grating couplers [5,6] as shown in Fig.7. The unidirectional optical coupler has very high coupling efficiency, compared with the other conventional grating couplers.

4. Conclusion

We proposed the high efficient unidirectional optical coupler for the TSPV in the optoelectronic 3D-LSI. We evaluated the unidirectional optical coupler by using FDTD simulator and showed that the unidirectional optical coupler can achieved 80% coupling efficiency. By using the coupler, we can realize very high-efficient input/output optical interconnection for optoelectronic 3D-LSI.

Acknowledgements

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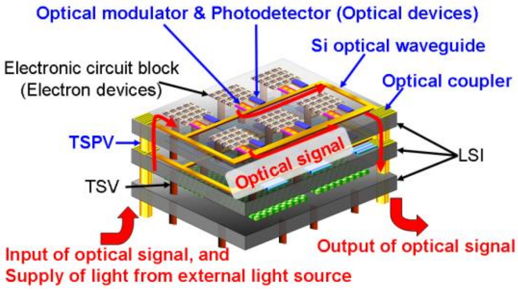

Fig. 1 Conceptual image of the optoelectronic 3D-LSI.

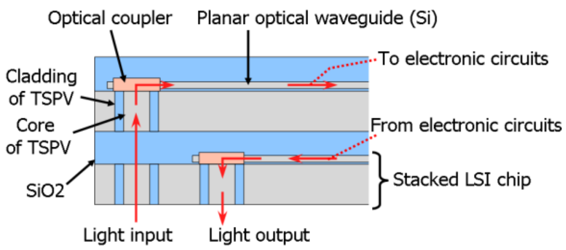

Fig. 2 Schematic drawing of the optical coupler between the TSPV and planar optical waveguide.

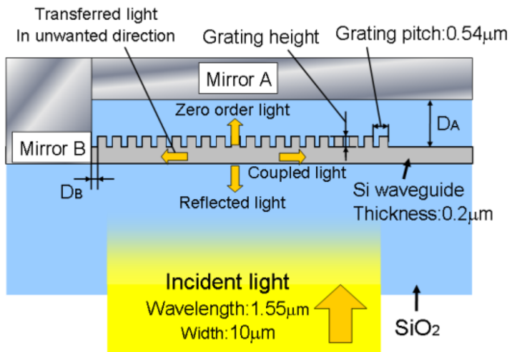

Fig. 3 Conceptual image of the high efficient unidirectional optical coupler for the TSPV.

References

[1] M. Koyanagi *et al.*, *Proc. IEEE*, **97** (2009) 49.
[2] D. A. B. Miller, *Proc. IEEE*, **97** (2009) 1166.
[3] A. Noriki, *et al.*, *Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials* (2010) 1198.
[4] H. Yamada, *et al.*, *Optics Express*, **19**, (2011) 698.
[5] R. Bruck *et al., Applied optics*, **49**, (2010), 1972.
[6] G. Maire *et al.*, *Optics express*, **16**, (2008), 328.

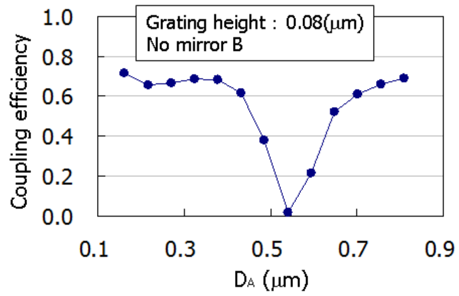

Fig. 4 Coupling efficiency of the unidirectional optical coupler as a function of D_A.

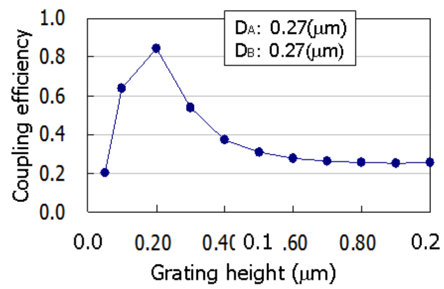

Fig. 5 Coupling efficiency of the unidirectional optical coupler as a function of grating height.

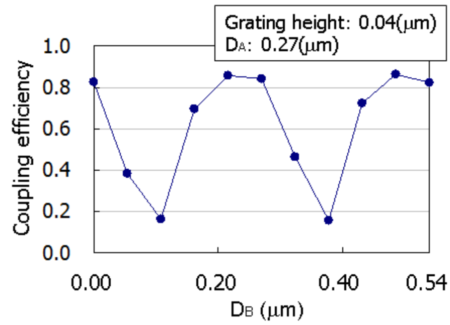

Fig. 6 Coupling efficiency of the unidirectional optical coupler as a function of D_B.

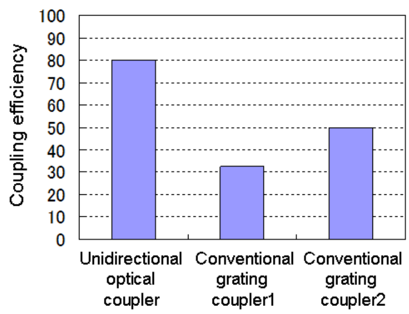

Fig. 7 Coupling efficiency comparison between the unidirectional optical coupler and the other conventional grating couplers.