Efficient chip-to-chip silicon grating coupler with high alignment tolerance at O-band

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***Abstract*—We theoretically investigate an O-band efficient and tolerant chip-to-chip silicon grating coupler with the bottom reflector. The coupling efficiency is increased greatly with the added bottom reflector, reaching a coupling efficiency of 91.2% (-0.4 dB) at 1316 nm wavelength. The 3-dB alignment tolerance in the x direction of 23 μm and 3.5-dB tolerance exceeding 35 μm are achieved thanks to the waveguiding effect constructed by two reflectors.**

Keywords—grating coupler, optical coupling, chip-to-chip

I. Introduction

The demand for high-speed and low-power data exchange has led to the development of inter-chip optical interconnection technology [1]. To realize the effective optical coupling between different chips, various methods such as grating coupling, butt coupling and adiabatic coupling have been proposed [2-4]. Despite its relatively small spectral bandwidth, the grating coupling has advantages of simple design, loose placement requirement and capability of wafer-scale testing, making it attractive in some applications with low bandwidth requirements. Several silicon grating couplers have been developed for chip-to-chip optical coupling systems [2,5]. However, the coupling efficiency in these coupling systems is quite limited due to the lack of optimization for optical leakage issues. Besides, the alignment tolerance still needs to be further improved, which is essential for most optical coupling systems.

In this work, we theoretically investigate an efficient chip-to-chip grating coupler with high alignment tolerance at O-band. The optical leakage issue is resolved by adding a metal reflector underneath the silicon layer, leading to a highly efficient coupling between two grating couplers. Through optimizing the grating period, grating duty and the thickness of the SiO_2 buried oxide (Box) layer, the simulation results show an optimized efficiency reaching 91.2% (-0.4 dB) at O-band, which has a significant improvement compared with the grating coupler without the bottom reflector. In addition to its high efficiency, the designed grating coupler also shows a considerable tolerance enhancement with a 3-dB tolerance of 23 μm in the x direction attributing to the waveguiding effect constructed by two reflectors in both grating couplers.

II. Design and Principle

To fast the simulation process, we use the 2.5D FDTD solver supported in the commercial software of Lumerical, which has been commonly used for 1D grating coupler design. Figure 1 shows the schematic of optical coupling between two identical grating couplers. The grating couplers are aligned in the x direction and close contact with each other in the y direction for the subsequent optimization of vertical coupling. The silicon structure is sandwiched between a SiO_2 Box layer and a SiO_2 cladding with the refractive index of 1.44 and thickness of 2 μm. An aurum layer with the thickness of 100 nm is placed below the Box layer acting as the bottom reflector. The grating length and etch depth is set to 15 μm and 70 nm, respectively. The simulation wavelength is fixed at 1310 nm. For vertical coupling, the phase matching condition at a given wavelength λ can be expressed as:

$$\frac{q}{\Lambda} = \frac{n_{eff}}{\lambda} \tag{1}$$

where q is the diffraction order, Λ is the grating period, and n_{eff} is the effective refractive index the of propagating TE mode in the silicon waveguide. For the first-order diffraction with the wavelength of 1310 nm, the grating period is calculated to be about 468 nm.

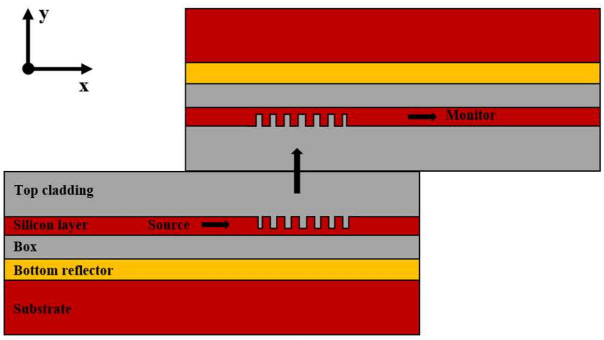

Fig. 1. Schematic of chip-to-chip optical coupling via grating couplers with the bottom reflector.

III. Results and Analysis

For comparison, we first optimized the grating coupler without the bottom reflector for the grating-to-grating optical coupling. The grating period, duty and thickness of the Box layer (d_box) are optimized simultaneously using the particle swarm optimization algorithm. Using the optimized parameters, the wavelength response of coupling loss was obtained, as shown in Fig. 2(a). The minimal coupling loss is as high as -4.8 dB at 1312 nm. Figure 2(b) shows the electric field intensity distribution in the x-y plane, which confirms the optical leakage leading to the high coupling loss. Unlike fiberto-chip coupling, grating-to-grating coupling shows a relatively large bandwidth (1dB bandwidth:~85 nm) due to the coupling angle matching which relieves the wavelength dependence of grating coupling [5].

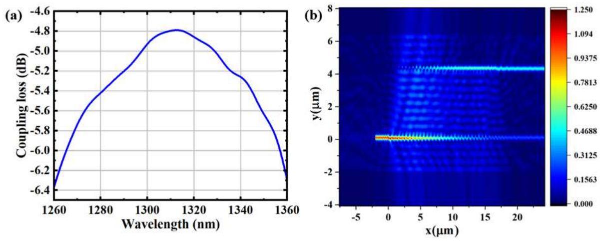

Fig. 2. Simulated (a) coupling loss and (b) the electric field intensity distribution in the x-y plane for the optimized grating coupler without the bottom reflector.

Next, we reconducted the simulation model by adding a bottom reflector underneath the Box layer and redoing the optimization process. The optimized parameters of the period, duty and d_box are 534 nm, 0.81 and 3.07 μm respectively. The simulation results under optimized parameters are shown in Fig. 3. Due to the presence of the bottom reflector, the optical leakage is effectively suppressed, leading to the minimal coupling loss of -0.4 dB. The 1-dB bandwidth is about 35 nm, which is relatively small compared with that of the grating coupler without the bottom reflector. However, this bandwidth is acceptable for many applications considering such high efficiency.

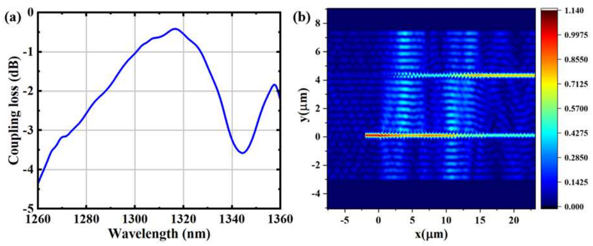

Fig. 3. Simulated (a) coupling loss and (b) the electric field intensity distribution in the x-y plane for the optimized grating coupler with the bottom reflector.

Further, we investigated the alignment tolerance in the x and y directions by changing the relative position of two grating couplers, respectively. The refractive index of the simulation environment is set to 1.44 which corresponds to that of the refractive index matching liquid commonly used in practice. Figure 4 shows the simulation results for the optimized grating coupler with and without the bottom reflector discussed before. The relative displacement corresponding to the lowest coupling loss is not zero for both cases, which means that the perfect vertical coupling is not achieved in these grating couplers with the above-optimized parameters, which can also be observed in Fig. 2(b) and Fig. 3(b). For the grating coupler without the bottom reflector, the coupling loss variation in the x direction shows a 1-dB tolerance of 4.87 μm and 3-dB tolerance of 10.77 μm. For the grating coupler with the bottom reflector, the results are dramatically different. In addition to the 1-dB tolerance increased to 9.06 μm, the coupling loss exhibits a gradual insensitivity to the relative displacement larger than 13 μm in the x direction, resulting in the 3-dB tolerance reaching 23 μm and 3.5 dB tolerance exceeding 35 μm. This can be attributed to the waveguiding effect constructed by the two reflectors in both grating couplers, which can also be confirmed by the electric field intensity distribution shown in Fig. 4(c) where the relative displacement in the x direction is set to 20 μm. Although two grating couplers are completely staggered when the relative displacement in the x direction exceeds 15 μm, the diffracted light from the lower grating coupler will eventually incident on the upper grating coupler due to the forward transmission of light achieved by reflection, ultimately achieving a considerable coupling efficiency. Figure 4(d) shows the coupling loss variation with the relative displacement in the y direction. The curves in Fig. 4(d) exhibit the periodic characteristic originating from the Fabry–Perot (F-P) effect and a limited alignment tolerance in the y direction is obtained as in the previous report [2]. It is worth noting that the F-P effect can be mitigated significantly by properly controlling the angle formed between two grating couplers, leading to a relatively loose tolerance in practice.

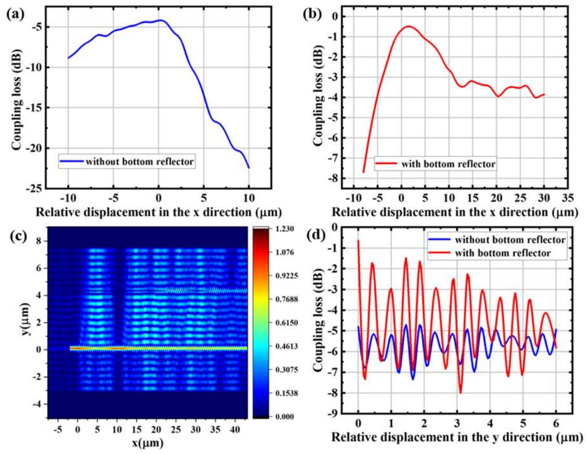

Fig. 4. (a)-(b) Variation of coupling efficiency with respect to relative displacement in the x direction for grating couping with and without reflectors. (c) The electric field intensity distribution in the x-y plane when the relative displacement in the x direction is set to 20 μm. (d) Variation of coupling efficiency with respect to relative displacement in the y direction for grating couping with and without reflectors.

IV. Conclusion

In conclusion, we demonstrate an efficient and tolerant chip-to-chip optical coupling method leveraging the grating couplers with bottom reflectors. Benefit from the elimination of optical leakage and the waveguiding effect constructed by two reflectors, coupling loss of -0.4 dB and 3-dB alignment tolerance in the x direction of 23 μm are achieved, which has a great improvement compared with the coupling scheme using reflector-free grating couplers. The grating-to-grating coupling also shows a 1-dB spectral bandwidth of 35 nm, which makes it valuable in optical interconnection applications.

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