Vertical-coupling optical interface for on-chip optical interconnection

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Abstract: We present a vertical-coupling optical interface with a grating coupler for transmitting and receiving optical signals between single-mode optical fibers and microphotonic waveguides with a view to realize on-chip optical interconnection. The optical interface consisting of a simple grating structure with a reflective mirror and an optical power combiner exhibits high optical coupling efficiency and wide tolerance range for the misalignment of optical fibers. The optical interface exhibits high coupling efficiency even if the optical input is almost vertical to the chip surface.

OCIS codes: (050.0050) Diffraction and gratings; (130.0130) Integrated optics.

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1. Introduction

Optical coupling between optical fibers and optical waveguides remains a crucial issue in integrated optics or on-chip optical interconnection [1–3]. Numerous studies on optical interfaces have shown that optical signals can be transmitted between optical waveguides on large-scale integration (LSI) chips and optical components outside a chip, such as optical fibers. Grating couplers that can direct light waves irradiated perpendicular to the chip surface toward the optical waveguide have been widely studied [4–9] as optical interfaces. High optical coupling efficiencies and a wide operating wavelength range have been obtained when

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optical interfaces with such grating couplers have been used. However, complicated grating structures [4,5] or oblique incidence configurations [5–8] have been required with these optical interfaces in order to obtain high optical coupling efficiencies. Therefore, it is difficult to fabricate such optical interfaces. Occasionally, special treatment of the optical connectors is required, such as the oblique polishing of the facets of optical fibers.

In this paper, we propose an optical interface with a grating coupler that can direct light waves irradiated almost perpendicular to the chip surface toward the waveguides with high efficiency. Further, the grating coupler used has a simple grating structure allowing for easy fabrication.

2. Structure and operation of interface

The optical interface consists of a grating coupler with the size several micrometers square, two mode converters, a power combiner, and optical waveguides that connect the mode converters and the power combiner. The overall view of the optical interface and the close-up of the grating coupler are shown in Fig. 1. The operation of this optical interface is explained as follows. When a light beam is irradiated to the grating coupler, some part of the optical power of the light beam is diffracted along two in-plane oppositely oriented directions by the second-order grating on account of the structural symmetry of the grating coupler. These diffracted light waves are directed to the mode converters and adiabatically converted to the mode sizes of the waveguides. Then, the light waves are directed toward the optical power combiner by the optical waveguides. When light waves from both the mode converters are combined in the same phase, the output power from the power combiner becomes double of that from a single mode converter. In order to collect the optical power passing through the grating and to couple the reflected light wave again to the grating, a reflective mirror is placed beneath the grating, as shown in the inset of Fig. 1. The optical coupling efficiency is drastically improved because of the reflective mirror, as described later.

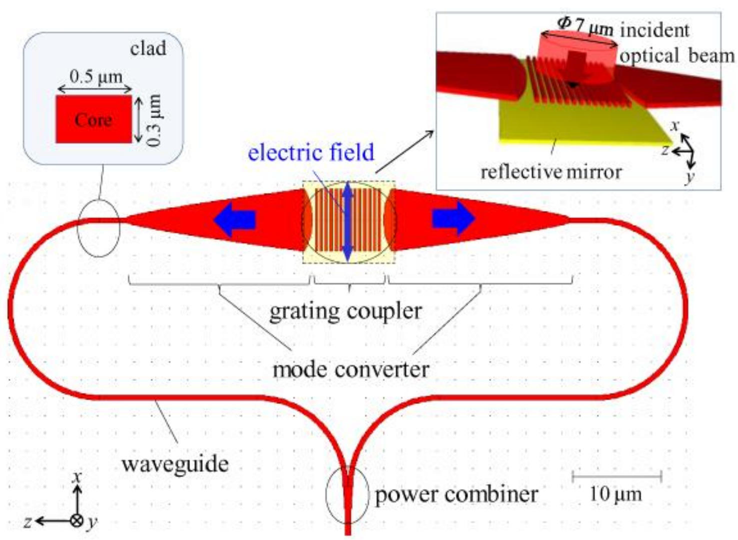

Fig. 1. Structure of vertical-coupling optical interface.

3. Theoretical analysis

We theoretically estimate the optical coupling efficiency of the optical interface using the following procedure. First, we calculate the diffraction efficiency of the grating by a 3D finite-difference time-domain (FDTD) method. Figure 2 shows the cross-sectional structure of the grating portion. The grating consists of a simple line-and-space structure with the same aspect ratio for line width and space. The line portion consists of a high-index material (n = 1.9), which is also used to construct the core of the waveguide. The space portion consists of a low-index material (n = 1.4), which is also used to construct the under-cladding layer of the waveguide. The upper-cladding layer of the waveguide is composed of another low-index material (n = 1.46). The thickness of the grating h is 300 nm, and the period of the grating is designed as Λ = 565 nm. The grating coupler is operated at a wavelength of around 850 nm. Each line and space repeats after 15.5 cycles, and therefore, the length of the grating portion is approximately 8.78 μm. A fully reflective mirror is placed 790 nm beneath the grating (d = 790 nm). We should note that this grating coupler only works when the electric field vector of the incident light beam is parallel to the grating and not in the case of light beams with other polarization. Therefore, a polarization diversity grating [9] or polarization maintaining optical fiber might be required for practical use.

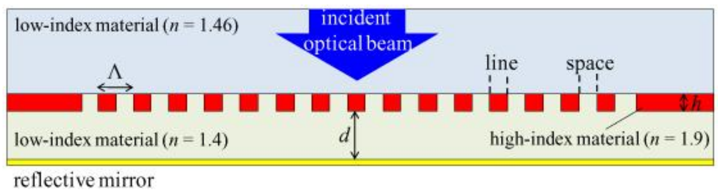

Fig. 2. Calculated cross-sectional structure of grating coupler.

Figure 3 shows the calculated electric field profile in a portion of the grating coupler and mode converters when an optical beam with Gaussian profile (ϕ = 7 μm) is irradiated on the grating. From this figure, we can observe that the irradiated optical beam is efficiently diffracted along two in-plane directions (left and right directions in the figure) by the grating coupler and converted to the size of the waveguide cross section by the mode converters. The sum of the diffracted optical power in both the directions is 57% of the optical power of the incident optical beam at the center wavelength of the operation. The diffraction efficiency strongly depends on the distance between the grating and the reflective mirror d. We calculated the diffraction efficiency as a function of the distance d. Figure 4 show the calculated d dependence of the diffraction efficiency as a parameter of the grating aspect ratio. The optimum value of d is around 790 nm when aspect ratio for the line width and space of the grating is 50:50.

Next, we calculated the loss in the power combiner and the waveguides and estimated the total optical coupling efficiency of this optical interface as 52%. This value is relatively high. Moreover, the grating used has a very simple structure, allowing for easy fabrication. The number of repeated lines and spaces in the grating structure is small, and wavelength dependence of the power combiner and waveguides are relatively lower than that of the grating, permitting a relatively wide operating wavelength range. Figure 5 shows calculated optical coupling efficiency for the whole structure. The operating wavelength range is about 60 nm for 3 dB down level of the optical coupling efficiency.

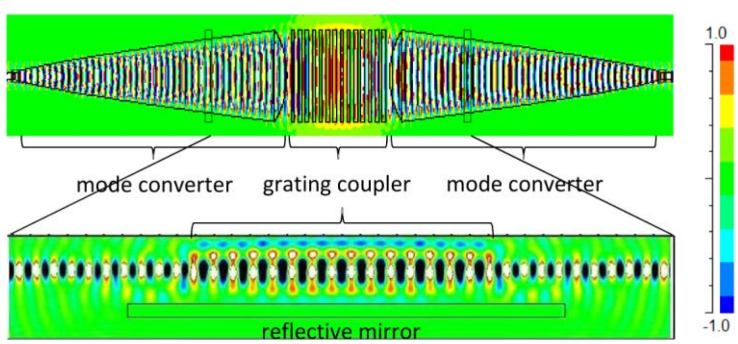

Fig. 3. Calculated electric field profile in grating coupler.

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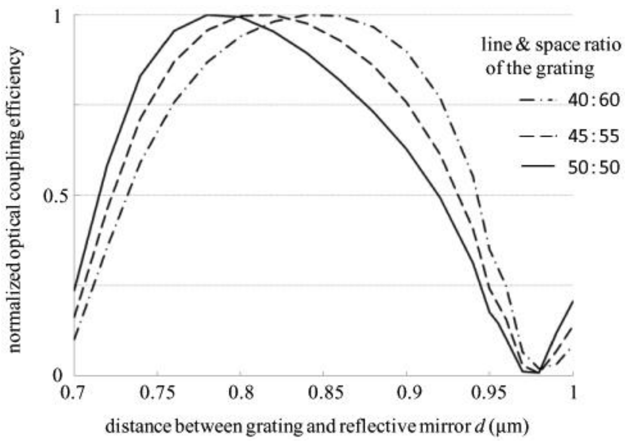

Fig. 4. Calculated diffraction efficiency as a function of the distance between the grating and the reflective mirror *d*.

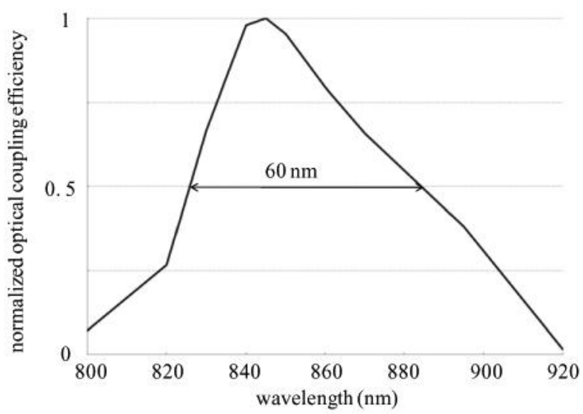

Fig. 5. Calculated operating wavelength range of whole structure.

Next, we calculated the tolerance for the misalignment of the input optical beam. Figure 6 shows the calculated tolerance for the misalignment of the optical beam with respect to the grating when the beam center was shifted from its center in both the *x*- (parallel to the grating) and *z*- (perpendicular to the grating) direction. We found that the tolerance for misalignment was ± 1.5 μm and ± 2 μm in the *x*- and *z*-directions, respectively, for a coupling loss increase of 1 dB. The tolerance is sufficiently large for practical use.

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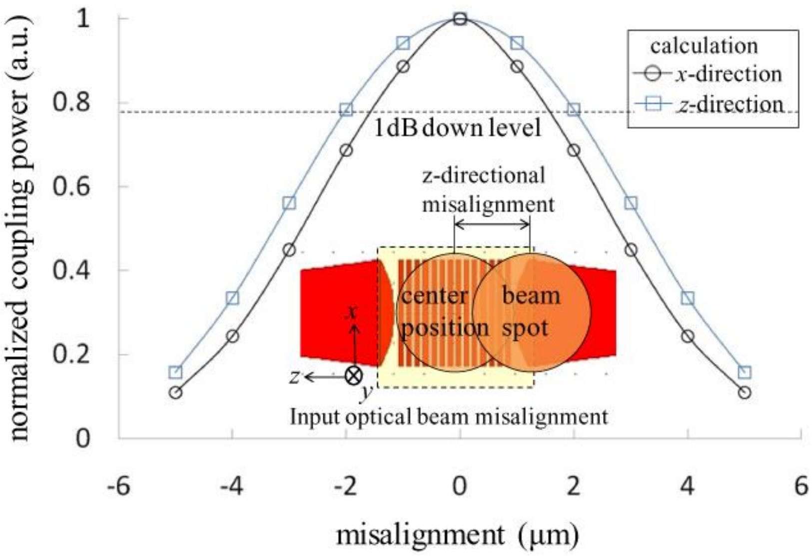

Fig. 6. Calculated tolerance for misalignment of optical beam with respect to grating.

4. Fabrication and measurement

We fabricated the optical interface with a SiON waveguide-based structure, which is a high-Δ channel waveguide fabricated using a SiON (n = 1.46 – 2.0) core and a silica cladding layer (n = 1.46) [2]. The cross-sectional size of the SiON waveguide core was 0.3 (H) × 0.5 (W) μm, and the waveguide could be bent to have a small radius of 20 μm. The grating consisted of the same material as the waveguide, and therefore the cross-section height of the SiON line was 0.3 μm. The refractive index of the SiON material used in this fabrication was 1.9. The grating was embedded in spin-on-giass (SOG) (n = 1.4), which served as the under-cladding material of the waveguide. The mode converter and power combiner were also made of SiON waveguides. Therefore, the grating coupler, mode converters, power combiner, and waveguides could be fabricated simultaneously with one process. In order to couple both the diffracted optical powers from the grating in the same phase, the length of the waveguides to the left and right sides of the interface differed by a half wavelength; this difference corresponded to 263 nm. Figure 7 shows the bottom view of the fabricated interface before placing the reflective mirror (a) and a close-up image of the grating and mode converter after evaporating the gold mirror (b). The area of the grating was 7 μm × 7 μm and the total size of the interface was 80 μm × 100 μm; thus, the interface is sufficiently small for applying on-chip optical interconnection. Figure 7(c) shows the image of the cross section of the grating coupler portion. As observed from the image, a simple line-and-space grating was successfully fabricated. The distance between the grating and the reflective mirror was 960 nm, which is considerably greater than the design value (790 nm).

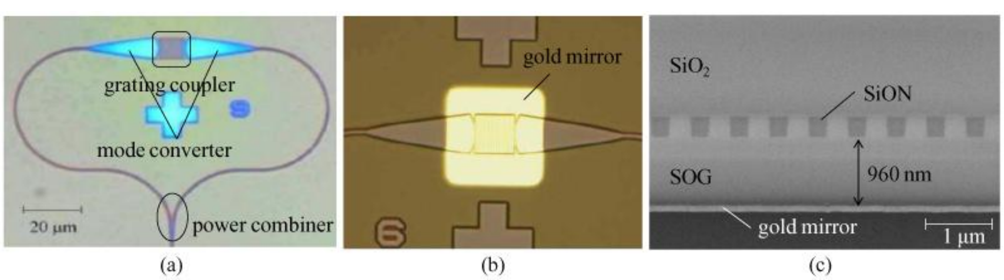

Fig. 7. View of fabricated interface: (a) Bottom view before evaporating gold mirror; (b) Bottom view of final structure, and (c) Cross section of grating coupler portion.

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We measured the optical coupling characteristics of the optical interface by irradiating a laser beam from a polarization-maintaining optical fiber onto the grating and evaluating the coupled optical power in the waveguide. The measured optical coupling efficiency was approximately 35%, which value can be explained by taking into account the discrepancy between the measured and designed *d* values, and the change of the grating line-and-space ratio. Figure 8 shows the measured tolerance for the misalignment of the optical beam with respect to the grating. We observed that our experimental result is in excellent agreement with our calculation.

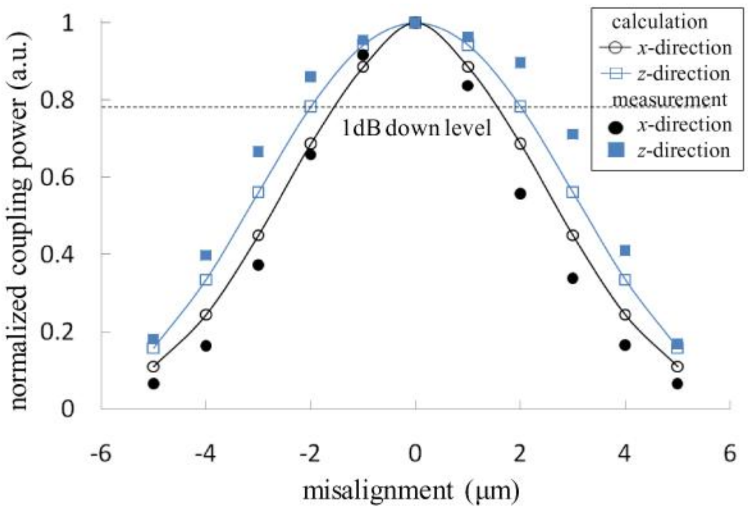

Fig. 8. Measured tolerance for misalignment of optical beam to grating.

5. Conclusion

We proposed an optical interface that can direct optical beams irradiated almost-perpendicular to the chip surface toward the waveguide on the chip. We theoretically and experimentally determined that the proposed interface exhibits sufficiently high optical coupling efficiency and wide tolerance for the misalignment of optical beams despite the very simple structure and consequent easy fabrication of the grating. Further improvement of the coupling efficiency will be expected by introducing more complicated grating structures [5]. The interface is less than 100 μm × 100 μm in size and therefore, sufficiently small to apply on-chip optical interconnection. In this study, we demonstrated an optical interface operating at a wavelength of 850 nm. We expect to obtain high coupling efficiency even at a wavelength of 1.55 μm using silicon channel waveguides, so that these optical interfaces can be used in optical communication systems.

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