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Design of a High-efficiency Fiber-to-chip Coupler with Reflectors

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Abstract: In this paper, an inversely tapered coupler with Bragg reflectors is reported for the first time. With appropriately positioned reflecting structures, our fiber-to-chip coupler can more efficiently transmit the light from fiber to a waveguide in a photonic integrated circuit (PIC). A numerical simulation evaluated the coupler's efficiency with the reflector. Optimized parameters that maximize the efficiency of the coupler are also investigated. Simulation results show that the reflector with appropriate parameters enhances efficiency by up to 7 dB. Likewise, Bragg metal reflectors implemented by the conventional metallization process can also improve efficiency. It is also shown that the proposed reflector enhances the coupling efficiency in a double-tip taper coupler.

Keywords: Silicon nanophotonics, Coupler, Reflector, Design

1. Introduction

Silicon nanophotonic devices can manipulate optical signals within a very small area. Over the past decade, many studies have reported on the performance of silicon nanophotonic devices [1-3]. The optical circuits that transmit and process optical signals have also received attention, because they can overcome the limitations of conventional electrical circuits in terms of signal integrity and power consumption. Generally, a photonic integrated circuit (PIC) is coupled to an external source that supplies light in the infrared (IR) range (e.g. $\lambda \approx 1.55$ μm). Optical single-mode fiber (SMF) is commonly used as the external light source. However, there is a huge mismatch between the optical mode size of the SMF (mode field diameter ~10 μm) and that of the waveguide in the PIC (on the order of hundreds of nanometers). In addition, the difference in refractive indices between optical fiber (e.g. an effective group index of refraction=1.468, Corning SMF-28) and a silicon waveguide (n=3.475) also contributes to the mismatch of an effective refractive index. Because of these mismatches, the coupling efficiency between optical fiber and a silicon waveguide is very low (-20 ~ -40 dB) for direct coupling.

In order to improve the coupling efficiency, a proper coupler and termination method are required. The role of the fiber-to-chip coupler is to provide high efficiency by matching the optical mode size and an effective refractive index between the fiber and the waveguide. A coupling structure converting an optical mode size gradually (i.e. a taper coupler [4]) can be a solution to the mismatch issue. At the end of the taper coupler, the termination of optical fiber directly couples to a funnel-shaped waveguide end. The facet of the optical fiber and waveguide must be polished to reduce reflection and dispersion of light. Using a taper coupler is simple, but its fabrication difficulty and low coupling efficiency are disadvantageous for practical applications. In a taper coupler, the width and height of the funnel-shaped waveguide's end is an order of the SMF's mode field diameter (MFD). A three-dimensionally tapered coupler is too difficult to integrate with other optical components in a PIC [5].

Another coupling technique is to use an inversely tapered coupler [6]. An inverse taper where the tip is only several tens of nanometers wide reduces the effective-index mismatch by the evanescent field at the tip. This compact coupling method is widely used because of high efficiency and easy fabrication. But the coupling area of the inversely tapered coupler is too small to be coupled to

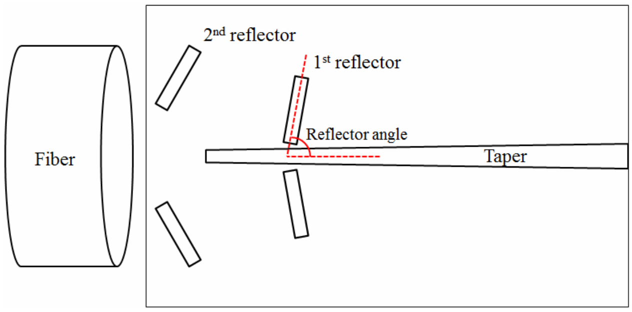

Fig. 1. A schematic top-view of an inverse taper coupler with reflectors.

conventionally terminated (cleaved and polished) optical fiber. To reduce the spot size of optical fiber's end, tapered-lensed fiber [7] is required. As a result, it is very difficult to align the tapered-lensed optical fiber to an inversely tapered coupler.

A grating coupler [8], which is based on Bragg refraction, is also popular. According to Bragg's law, the periodic patterns at the waveguide's ends scatter incident light from optical fiber's termination to the waveguide in a PIC. The advantage of the grating coupler is that it is vertical coupling, not in-plane. Therefore, there is no need to do mechanical PIC processing, such as dicing and facet polishing. However, the dependence on the wavelength and polarization of incident light can be disadvantageous in this coupling method.

There are other efficient ways of coupling optical fiber to the waveguide. For example, superimposed micro-ring [9], a parabolic reflector [10], metal cladding [11], and a prism [12] have been used. However, these methods are complicated in their fabrication processes.

The objective of these fiber-to-chip couplers is efficient transmission of light while keeping an easy-to-fabricate structure. Yet, none of the conventional coupling methods have met this goal. In this work, we propose a new fiber-to-chip coupler to enhance coupling efficiency while keeping easy fabrication and a large process margin. Then, the coupler is designed to have high coupling efficiency.

2. Design of an Inverse Taper Coupler with Reflectors

The dominant technique in fiber-to-chip coupling is in-plane coupling using an inversely tapered coupler. However, a conventional inverse taper coupler has the disadvantage of a small coupling area. To overcome the disadvantage, we propose an inverse taper coupler with reflectors. Fig. 1 displays its schematic layout. The first reflectors near the tip of an inverse taper reflect incident light from the termination of optical fiber to the tip, and the second reflectors again reflect the light from the first reflector to the taper's tip. The two sets of reflectors on each side are located symmetrically on the same plane as the inversely tapered waveguide.

Each reflector is based on Bragg reflection at a silicon grating [13] at a specific pitch. Silicon Bragg reflectors and the inverse taper coupler can be patterned simultaneously, with a simple photolithography and chemical etching process. The first reflectors, which are close to the taper, reflect the light that does not couple into the tip. The second reflectors accept light from the first reflectors and reflect the light to the tip of coupler, and the angle of the second reflectors relative to the taper forms a focal point in front of the tip. A set of second reflectors has enough of a gap for incident light to pass through and get to the coupler and the first reflectors. Since optimized parameters for the inverse taper and waveguide itself are already well known from previous research [14], they are set to appropriate values throughout the entire set of designs. The width of the coupler is gradually increased from 80 nm (optimized to TE mode polarization) to 450 nm (a typical silicon waveguide dimension), and its length is fixed at 150 μm to reduce coupling loss through the taper.

Table 1 Optimized design parameters of the reflectors at a wavelength of 1.55 μm.

Design parameter	Optimized value
Pitch of grating	450 nm
Tooth width of grating	150 nm
1st reflector: number of grating teeth	2 ea
1st reflector: space from taper center	500 nm
1st reflector: angle	85°
2nd reflector: number of grating teeth	3 ea
2nd reflector: space from taper center	2 μm
2nd reflector: angle	70°
Space between 1st and 2nd reflectors	7 μm
Length of reflectors	> 4 μm

3. Simulation Results

In order to evaluate improvements in coupling efficiency and to optimize parameters of the reflector's design in Fig. 1, a numerical simulation was performed using Multiphysics software from COMSOL Inc.

The design parameters providing maximum coupling efficiency were determined after conducting extensive simulations. In the simulations, it is assumed that the waveguide and reflector, which are made of silicon, are passivated by silicon dioxide (n=1.44). The optimized design parameters are summarized in Table 1 for a wavelength of 1.55 μm. Pitch of grating means the period of repetitive patterns, as shown in Fig. 2. The tooth width of the grating is also depicted in Fig. 2

In Fig. 2, a magnified top view of the proposed coupler with first and second reflectors is shown. The geometry regarding the reflectors in Fig. 2 is based on the dimensions in Table 1. The length of the reflectors is 4 μm.

Fig. 3 shows electric field distributions of an inverse tapered coupler without a reflector and with a reflector. This figure shows the superiority of the proposed coupler over a conventional inverse tapered coupler. The uncoupled light in the proposed structure is reduced

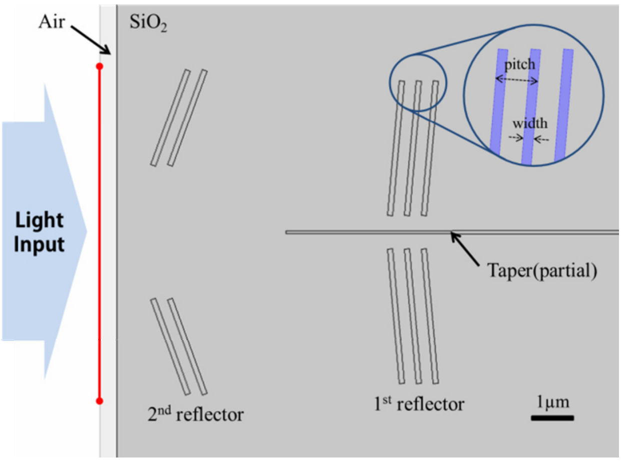

Fig. 2. Magnified top-view of the proposed coupler with reflectors.

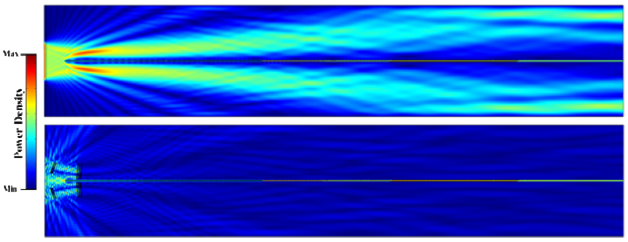

Fig. 3. Electric field distributions of an inverse tapered coupler without a reflector (top image) and with a reflector (bottom image).

significantly, which means that the light from the optical cable can be efficiently transmitted to the waveguide.

The coupling efficiency is defined using the S-parameter under this relation:

$$S_{21dB} = 20log10(|S_{21}|) \qquad (1)$$

where S_{21} is the forward voltage gain for the two-port network. The input port is the termination of the optical fiber, and the output port is the end of the taper that is connected to the waveguide opposite the fiber (see Fig. 1).

3.1 Dependence on Light Input Width

As mentioned in Section 1, a conventional inverse taper coupler has a small coupling area. Therefore, tapered-lensed optical fiber where spot size is smaller than cleaved fiber needs to be used. We investigated the relations between the coupling efficiency of our new coupling method and the input width of the incident light. The simulated efficiencies are plotted in a relative scale. Here, we set the minimum value (the efficiency of the coupler without reflectors at a light input width of 10 μm) among the simulation results to the reference value (0 dB). When there is no reflector near a coupler, the coupling efficiency of the inverse taper coupler decreases dramatically when increasing the width of incident light (solid circles in Fig. 4). The taper coupler with a reflector exhibits much improved efficiency (solid squares in Fig. 4) at all input field widths. In particular, at a light input width of ~10 μm, coupling efficiency improves by up to 7 dB when reflectors are adopted. In an inverse taper coupler with reflectors, the dependence of coupling efficiency on the input light width is much smaller than that of the coupler without the reflectors. The proposed coupler shows no appreciable difference in efficiency by changing the light input width from 3 μm to 10 μm. This indicates that our new coupler has a coupling area wide enough for coupling a cleaved SMF directly, resulting in a large process margin.

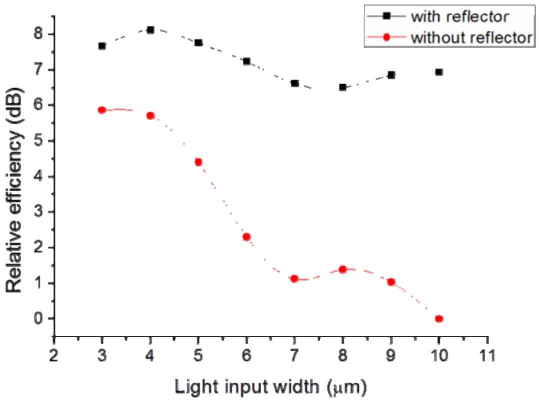

Fig. 4. Relative coupling efficiency versus light input width. The efficiency of the coupler without the reflectors at a light input width of 10 μm is set to 0 dB.

3.2 Misalignment Tolerance

In aligning the terminated optical fiber to a coupler, misalignment between the fiber and the taper is inevitable. So, a tolerance for the misalignment should be set aside. But a conventional inverse taper coupler that has a small coupling area should be coupled to a tapered-lensed fiber that has a small spot size of light. Here, a conventional coupler means a taper without reflectors. Consequently, the coupling efficiency of a conventional inverse taper coupler is changed, sensitive to misalignment between the fiber and the taper. Thus, a large coupling area and a change in coupling efficiency as small as possible for the light input width are required to ensure a wide range of misalignment tolerance. Section 3.2 investigates how the proposed coupling technique has a much wider coupling area than a conventional coupling method. Therefore, the proposed coupler can be coupled to a conventionally terminated SMF with high efficiency, in contrast to a conventional inverse taper coupler. Now, we compare the proposed and conventional couplers in terms of misalignment. Light input widths to the proposed and conventional couplers are 10 μm and 3 μm, respectively, which are the spot sizes of the optical mode at the end of a cleaved SMF and a tapered-lensed SMF.

Note that although a light input width of 3 μm in the proposed coupler gives slightly higher efficiency than a width of 10 μm, a light input width of 10 μm is adopted for the proposed coupler, because we avoid a process step to implement tapered-lensed optical fiber and achieve easy alignment. Since a width of 10 μm gives very poor efficiency in a conventional coupler, we adopted a width

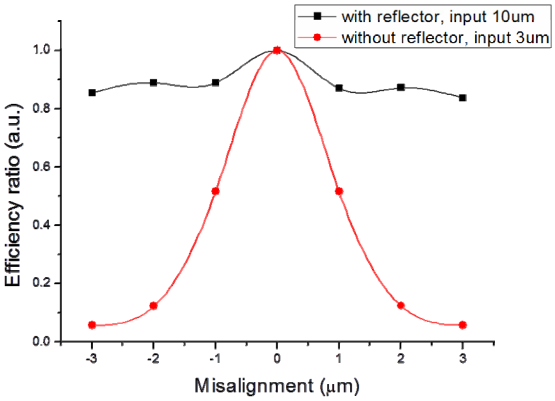

Fig. 5. Efficiency ratio of two different inverse taper couplers versus misalignment.

of 3 μm (the smallest size in Fig. 4). Fig. 5 shows the efficiency ratio of each coupling method when there is misalignment in the plane of the couplers. The efficiencies at non-zero misalignment are normalized to that of misalignment of 0 μm at each coupler.

In a conventional coupler (a taper without reflectors), the coupling efficiency is reduced by half when the misalignment is ±1 μm due to its narrow width of input light. Since the coupling efficiency is much less sensitive to misalignment for a wide width of incident light, the proposed coupler (a taper with reflectors) at a light input width of 10 μm shows nearly constant efficiency (over 84% to its maximum value) even when the misalignment changes from 0 to ±3 μm. Thus, the proposed coupling technique has a much wider coupling area, so that conventionally terminated optical fiber can be coupled with high efficiency and a large process margin in alignment.

3.3 Frequency Spectra

We also characterized the dependence of the proposed coupler on the frequency of the incident light. Because design parameters of reflectors are strongly related to the wavelength of incident light, the coupling efficiency of an inverse taper with reflectors is more sensitive to the wavelength of incident light than a conventional taper. As shown in Fig. 6, the frequency spectra of the coupling efficiency in the proposed coupler peaks at a wavelength of about 1.55 μm. Here, the input width of light is set to 10 μm. The peak value can be adjusted to any desired value by tuning the design parameters for reflectors.

3.4 Metal Reflector

A Bragg reflector made of silicon grating can be substituted for a metal reflector. As mentioned previously, the silicon Bragg reflector was selected to facilitate simple fabrication. But considering that the fabrication process of most PICs is compatible with that of a conventional CMOS circuit, a metal reflector can also be implemented with a conventional metallization process. Now, we replace a silicon Bragg reflector with patterned aluminum (the imaginary part of the refractive index, k, is 15.286) in the structure for numerical simulations. The metal reflector is single-wall, and its width is 450 nm. The differences in coupling efficiencies among the three different couplers are presented in Fig. 7.

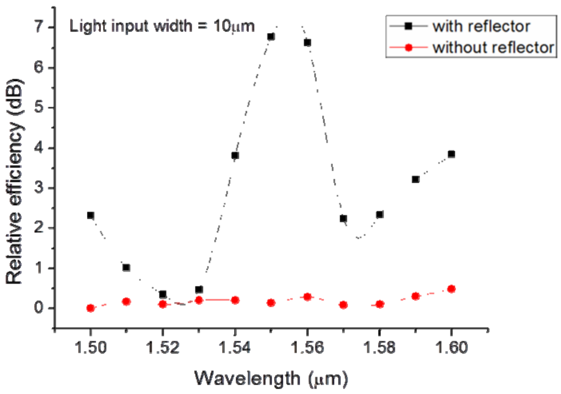

Fig. 6. Relative efficiency of two different couplers versus input wavelength. The input light width is fixed at 10 μm. The minimum efficiency in this figure is set to 0 dB as a reference for relative efficiency.

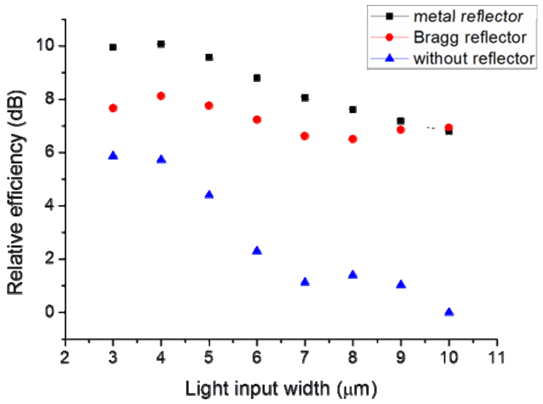

Fig. 7. Relative efficiencies of three different couplers according to light input width. The width of the metal reflector is 450 nm.

3.5 Application to Other Type of Coupler: Double Tip Coupler

The role of the proposed reflector (increasing coupling efficiency) can be observed in other types of couplers. To verify this, we replaced the single-tapered coupler with a double-tip coupler. It is well known that double-tip couplers have higher efficiency than single-tip couplers [15]. A schematic top view of a double-tip coupler is shown in Fig. 8. The optimized gap between the tip center is 600 nm. Each tip of the coupler is linearly tapered to the waveguide. So, the angle between the edges of the tapers is constant. Fig. 9 shows that the adoption of the reflector works more efficiently in a single-tip taper than a double-tip taper, especially with a greater width of light input. With the reflectors, there is no significant difference in efficiency between single-tip and double-tip couplers. This demonstrates that our coupling technique is a very effective way to couple a waveguide in a PIC to simply

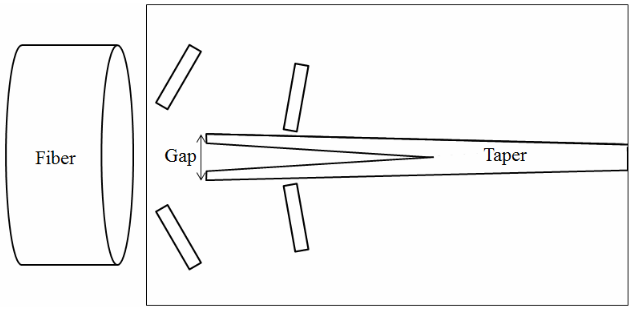

Fig. 8. A schematic top view of a double-tip coupler with reflectors.

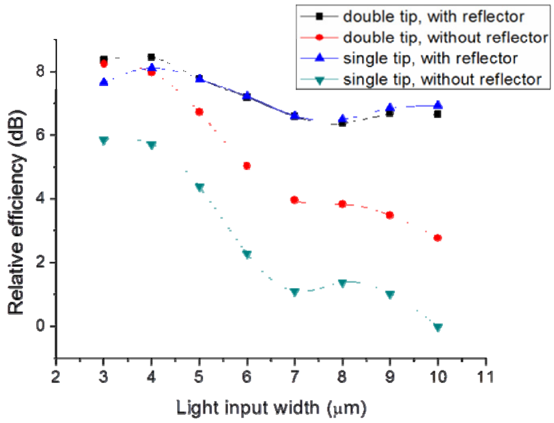

Fig. 9. Relative efficiencies of four different couplers according to light input width.

terminate optical fiber with high efficiency and a low sensitivity to misalignment.

4. Conclusion

We have proposed a new coupling structure by arranging optimized silicon Bragg reflectors or metal reflectors near the tip of an inversely tapered coupler. Our coupling method recycles incident light to enhance coupling efficiency by up to 7 dB, compared to that of a coupler without reflectors, and effectively enlarges the coupling area. According to the simulation results, our approach effectively couples conventionally terminated single-mode optical fiber to a photonic IC while retaining immunity to misalignment. We also investigated efficiency according to the frequency of input light in our coupling structure. The efficiency of our coupler according to frequency can be adjusted by tuning the design parameters for the reflectors. The techniques proposed in this paper could realize direct contact of optical fiber to a waveguide with efficient coupling of incident light.

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