Asymmetric Dielectric-Resonator Grating Coupler

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December 20, 2018

Abstract

We demonstrate a novel grating coupler design based on double asymmetric dielectric resonators to efficiently couple normally incident light to a single waveguide mode.

1 Introduction

Grating couplers are ubiquitous in integrated photonics for the conversion of free-space propagating light to guided light \[1\]. To achieve unidirectional propagation, grating couplers are typically designed for obliquely incident light. This strategy, however, can lead to alignment difficulty and poor stability. For this reason, there have been significant efforts to design efficient grating couplers that work at normal incidence \[2\]. Typical coupling efficiencies for such couplers are much lower than their oblique angle counterparts, and limited \textit{a priori} by their lack of directionality.

There are different strategies to design normal-incidence grating couplers. The simplest one is to use a momentum-matched binary groove grating. However, such a structure wastes power both in the undesired direction of the waveguide and in the zeroth-order beams. To achieve unidirectionality, one can use a blazed grating with asymmetric saw-tooth profile. This suppresses the undesired coupled mode, but involves complex fabrication. A closely related strategy involves modulating the width of the binary grating elements to achieve unidirectionality, but such designs still suffers from loss due to the zeroth-order diffraction orders \[3\]. To reduce such loss, one may use Bragg reflectors or metallic mirrors below the waveguide structure, but this requires additional layers and may be incompatible with the overall fabrication process \[4\].

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All of these grating coupler designs involve non-resonating grating elements. Recently, it was experimentally demonstrated that asymmetric V-shaped plasmonic nano-antennas could be used to realize compact normal-incidence couplers due to their strongly resonating behaviour [5]. Coupling efficiencies remain low, however, given that such designs suffers from plasmonic losses.

Here, we propose a compact dielectric grating coupler, which solves the aforementioned issues: 1) it uses double – horizontal and vertical – symmetry breaking, and hence suppresses all of the undesired diffraction orders; 2) it is composed of purely dielectric resonators, and hence has negligible absorption loss; 3) it is composed of a single patterned layer for simple fabrication.

2 Design Rationale

We designed a single-mode silicon waveguide on buried oxide layer (BOX) based on Silicon-on-Insulator (SOI) technology for 1550 nm. The waveguide operates in the fundamental transverse electric mode. The period required for the grating to couple normally-incident light to the guided mode light is calculated from \( \Lambda = \frac{\lambda}{n_{\text{eff}}} \) to be \( \sim 600 \) nm, where \( n_{\text{eff}} \) is the effective refractive index obtained from the slab waveguide dispersion relation.

By applying the reciprocity principle, the grating coupler problem can be transformed into the equivalent, but simpler analysis of a grating decoupler. First, the waveguide coupled to the grating should be impedance-matched only at one of its ends, and fully reflective at its other end, which requires symmetry breaking in the horizontal plane. Second, the grating should decouple light only toward the top, which requires symmetry breaking in the vertical direction.

To break the horizontal-plane symmetry, we designed a \( \pi \)-shaped silicon resonator. Due to the presence of two different dielectric media at both sides of the resonators, air at the top and silicon-BOX at the bottom, the overall resonator structure is also vertically asymmetric, and hence radiates with different phases toward the top and the bottom [6, 7]. However, this does not resolve the issue of the zeroth-order beam, since all the resonators radiate with same phase toward the bottom. In addition, these resonators, when coupled to the waveguide, radiate more effectively toward the bottom than toward the top due to a higher field concentration in the substrate as compared to air. To resolve these two issues, we inserted a cylindrical hole in every two \( \pi \)-resonator in such a fashion that the phases radiated toward the bottom by the holey and holeless resonators are out-of-phase; as a result the radiation toward the bottom is significantly suppressed. The combined structure of both kind of \( \pi \)-resonators is shown in figure 1a.

3 Results

We then performed full-wave simulation of the grating coupler using periodic boundary-condition environment in CST Microwave Studio. We chose a 6.5 \( \mu \)m long grating coupler with 11 dielectric resonators to demonstrate a compact coupler design. In our reciprocal analysis, the waveguide reflects 7% power
Figure 1: Proposed asymmetric dielectric-resonator grating coupler (a) Structure, (b) Poynting vector plot for Gaussian beam input.

from the desired end (Port-1), whereas it reflects 75% power when fed from the undesired end (Port-2). In addition, when fed from the desired end, 10% of the power is transmitted to the undesired end of the waveguide. This can be minimized to an almost negligible amount by choosing a longer coupler. Note that a small decoupling/coupling length is achieved due to the use of strongly resonating elements and we could also realize a longer decoupling/coupling length of 10 \( \mu \text{m} \) or more to match arbitrary free-space spot sizes by using moderately or weakly resonating elements. The remaining 93% power coming in from the desired end of waveguide splits into 2.5:1 between the radiation toward the top and the bottom. It should be noted that before introducing cylindrical holes in every two \( \pi \)-resonators, the splitting ratio was 1:1.8 suggesting higher field concentration in the substrate.

Finally, to calculate the coupling efficiency, we irradiated the grating coupler with a Gaussian input beam, as shown in figure 1b, with a 2.5 \( \mu \text{m} \) radius spot size centered on grating coupler. Our simulation results show 40% in-coupling efficiency to the desired waveguide direction. We should highlight that the radiation field profile during the inverse design is not matched to a that of a Gaussian input beam. In our future work, we will work on further increasing the overall efficiency by laterally adjusting the grating elements to match the desired free-space profile.
4 Conclusion

A grating coupler based on asymmetric-dielectric-resonators for normally incident light has been introduced. The technique provides flexibility in terms of coupling length and efficiency due to the inclusion of resonating dielectric grating elements.

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