Silicon Waveguide Grating Couplers with Engineered Coupling Strength for Optimized Coupling

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***Abstract*—We describe simulation and experimental results of gratings for coupling between optical fibers and nanophotonic waveguides. The coupling strength was engineered to obtained Gaussian-like output profile. 1.2dB coupling loss is achieved to single-mode fibers. Preliminary experimental result for coupling with vertical fiber with chirped grating gives a 3dB coupling loss.**

Keywords - grating coupler; silicon-on-insulator; integrated photonics; chirped grating

I. INTRODUCTION

Highly integrated photonic circuits could be realized at low cost based on silicon-on-insulator (SOI), because of small size made possible by the high refractive index contrast between the waveguide core material (silicon) and the cladding materials (air or silicon dioxide), and the availability of established semiconductor (CMOS) nanofabrication technology. End fire coupling techniques with adiabatic tapers [1] have achieved highly efficient coupling between small core area optical fibers and nanophotonic SOI waveguides. Diffractive waveguide grating couplers [2] has also been actively researched and coupling losses as low as 1.6dB were recently achieved with a high index polysilicon overlay [3]. Compared with the alternative coupling techniques, waveguide grating couplers are of immense practical interest because of their many advantages, including large alignment tolerance, simpler fabrication process since they do not require polishing of facets, and the flexibility to be placed anywhere on the chip.

The coupling efficiency of grating couplers is mainly limited by two factors. One is the bi-directional nature of grating diffraction. A large fraction of the optical power in the SOI waveguide is coupled downwards into the substrate instead of upwards to the optical fiber. Additional structures such as a polysilicon overlay [3] or a substrate mirror [4] were demonstrated to guide more light towards the fiber. Another factor that limits the coupling efficiency is the mode mismatch between the field profiles of diffracted light from waveguide grating and the fiber mode. An exponentially decaying field profile is expected when diffracted from a uniform grating, and this would theoretically limit the coupling efficiency to a maximum of 80% for coupling to the Gaussian-like mode profile of an optical fiber [5]. It was suggested that Gaussian-like output profile from SOI grating couplers may be achieved by varying the fill factor of the grating [6], but to our knowledge this has not been previously implemented.

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In this paper, we describe the simulation and experimental measurement results of highly efficient diffractive gratings for coupling between perfectly vertical ($\theta = 0°$) or slightly titled optical fiber and nanophotonic waveguide as shown in Fig.1a, whose fill factors are engineered to achieve Gaussian-like output profile.

II. SIMULATION & EXPERMENTAL RESULTS

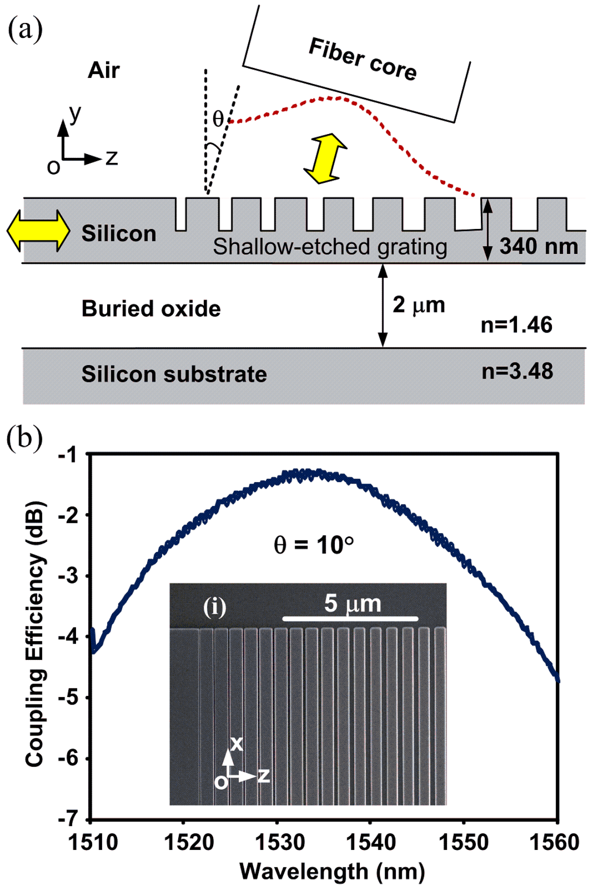

Fig.1. (a) Schematic of the fabricated grating couplers. (b) The experimentally measured coupling efficiency of the grating coupler with engineered fill factor, coupling between titled optical fiber ($\theta = 10°$) and nanophotonic waveguide. From the best measurement result, -1.2dB efficiency is achieved at 1534nm. (i) The inset shows a SEM image of the fabricated grating coupler.

The grating couplers were fabricated on a SOI wafer using electron beam lithography with 340nm thick top silicon layer and 2μm thick buried oxide. Grating was formed by 200nm shallow etch. 2D FDTD simulation was used to verify and optimize the coupler designs. The directionality (defined as the portion of the light power coupled into fiber normalized with respect to the total coupled optical power) of the grating can be optimized up to 0.87 according to simulations with the configuration listed above. We went beyond the strict single-mode waveguide thickness constraint and used a more optimum waveguide thickness and etch depth. Although the waveguide thickness used may support a weakly guided first order mode, for most device applications, the grating coupler itself can act as an effective mode filter for both the input and output coupling and thus only the fundamental mode is present.

The fundamental mode of the nanophotonic waveguide is first expanded laterally (in x-axis) by an adiabatic taper to a 10.4μm wide waveguide which have a lateral mode size similar to the single mode fiber. The light would then be diffracted upward into the optical fiber by the grating; whose fill factor was varied according to our calculation. So that the coupling strength was engineered and a Gaussian-like output field profile was realized. When coupling to a slight titled ($\theta = 10°$) standard single mode optical fiber, the grating coupler achieved a loss of only 1.2dB from the TE mode in a 450nm (wide) by 340nm (thick) SOI waveguide. This result is the highest coupling efficiency reported to date for waveguide grating couplers.

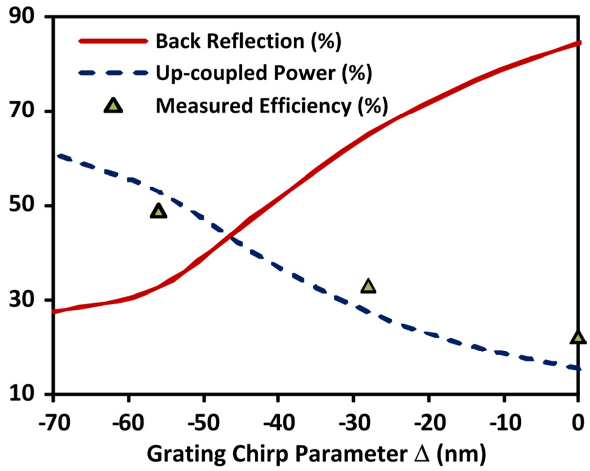

Fig.2. The simulated back reflection and up-coupled power into fiber are plotted with different grating chirped parameter. Experimentally measured coupling efficiencies are also plotted.

With slightly tilted fiber, we found that varying the fill factor of grating couplers is also able to eliminate the small back reflection caused by the comparatively large index step of the grating. But back reflection would still dominate (> 80%) when we designed the grating for coupling to perfectly vertical optical fiber. Because the vertical coupling scheme (without fiber tilting) would be more preferable for low cost photonic packaging process, preliminary work on applying linearly chirped grating to reduce the back reflection [7] was carried out with the constraint of maintaining a Gaussian-like output profile and keeping the fiber vertical to the chip surface.

Simulation result for the chirped grating coupler is plotted in Fig.2. Because we are using fill factor f (ratio of the etched groove over period) ranging from 0.08 to 0.4 to engineer the coupling strength of the grating coupler along z-axis. The average effective index of the grating region would also change with f. According to phase matching condition, the grating period Λ need to be change from 520nm to 580nm for different f in the design for vertical coupling at 1550nm wavelength. Similar to [7], we could define a grating chirp parameter Δ as the maximum deviation of the change applied to the first and last grating periods of the chirped section. The negative sign means the change of each period is decreasing. For example, if $\Delta = -40$nm, the first period would be change from 520nm to 540nm, and the last period would be changed from 580nm to 560nm. By linearly chirping the grating period (reducing Δ from 0), the back reflection can be reduced significantly. The coupling efficiency is enhanced as shown in Fig.2. Preliminary experimental results showed a 3dB coupling loss with $\Delta = -56$nm. The Fabry-Perot resonance was found to be reduced from 11dB to 2.6dB for a short waveguide with two grating couples at both ends, indicating a significant reduction of the back reflection. Further improvement of the design is under way, as we found that the coupling strength increased abruptly when reducing the coupling angle θ. Thus the output profile of the vertical grating coupler was distorted.

III. Conclusion

We experimentally demostrated waveguide grating couplers with 1.2dB and 3dB coupling loss with off-vertical and vertical optical fiber respectivley. The fill factor is varied to achieve Gassian-like output profile from the waveguide grating. Back reflection was reduced by a linear chirp of the grating period to enhance the coupling efficiency with vertical optical fiber. Further improvement is under way.

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