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Highly Efficient Grating Coupler for Silicon Nitride Photonics with Large Fabrication Tolerance

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Abstract: We demonstrate low-loss fiber-to-chip coupling via a-Si grating couplers on top of SiN waveguides for C-band TE light. The suggested simple scheme is fabrication tolerant and offers a path towards coupling efficiencies above -1 dB.

1. Introduction

Silicon nitride (SiN) has emerged as a viable platform for integrated photonics [1], with advantages such as ultra-low propagation losses of 5.5 dB/m for highly confined modes in planar waveguides [2], a wide transparency window [3], a low thermo-optic coefficient [4], and negligible two-photon absorption combined with a weak Kerr effect [5].

Efficient fiber-to-chip coupling can be obtained via edge couplers facilitated by the large mode size yielding coupling losses below 1 dB [6]. On the other hand, vertical coupling via gratings poses an undeniable advantage, since it can be freely placed and enables higher device densities. This is essential to achieve small footprints and tape-outs on multi-project wafers with limited space. However, the low refractive index difference between SiN and SiO_2 dissents an efficient grating design. In practice, single-layer gratings typically have losses exceeding 4 dB for SiN [7]. To improve the efficiency, Bragg reflector stacks have been applied beneath the SiN waveguides [8-11]. This way, coupling losses were reduced to 1.75 dB in experiment [11], and to 0.66 dB in simulations [12]. These impressive results though come at the price of fabrication complexity and incompatibility with standard processes.

To solve the tradeoff between complexity and efficiency in SiN grating couplers, we introduce a-Si gratings [13, 14], adapted to the low-loss SiN passive platform. Our design exploits a simple fabrication process with relaxed tolerances and we demonstrate a coupling efficiency (CE) of -2 dB in simulation with a 40 nm wide 1-dB bandwidth, and of -2.7 dB in experiment. We also show the potential of the technology towards lowest coupling losses of 0.5 dB.

2. Design, Simulation, Characterization and Fabrication

Fig. 1(a) shows the schematic of the coupler with an 800-nm-thick SiN waveguide layer, a roughly 120 nm interlayer oxide (ILO) as a buffer and a amorphous silicon (a-Si) layer with the design parameters. The a-Si height $h_{\text{Si}} = 290$ nm, grating period $\Lambda = 886$ nm and its fill factor $L_O/(L_O + L_E) = 0.325$ have been determined by optimizations with 2D finite-difference time-domain (FDTD) simulations. Fig. 1(b) shows an optical microscope image of the fabricated devices highlighting the placement with sufficient in-plane alignment tolerance.

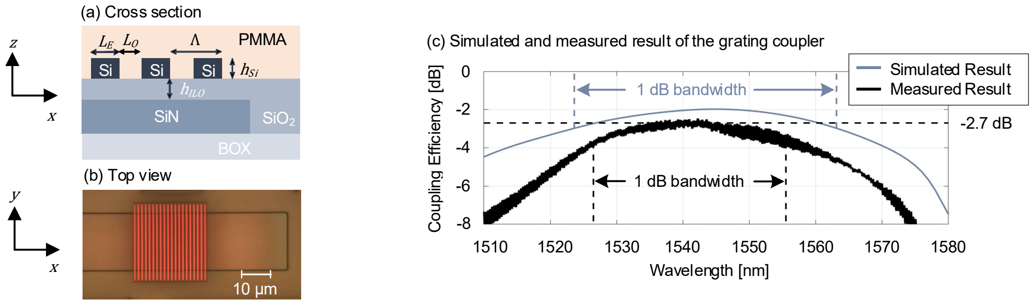

Fig. 1. SiN waveguide grating coupler concept, fabrication, and performance. (a) Cross-section of the fabricated grating coupler. (b) Top view of the fabricated grating coupler highlighting the ultra-relaxed horizontal alignment tolerance. (c) Measured CE with a peak transmission of -2.7 dB and a 29 nm 1-dB bandwidth (black). Simulations are promise with -2 dB CE and a 1-dB bandwidth of 40 nm (light blue).

Fig. 1(c) shows the measured and simulated CE of a single grating coupler, with a maximum CE of -2.7 dB in measurement. This is to the best of the authors' knowledge the highest reported coupler efficiency for a fully etched grating coupler into SiN waveguides when complicated reflectors are omitted. The 1-dB bandwidth of the grating is 40 nm in simulation and 29 nm in experiment.

The above structures have been fabricated by placing output gratings structures on top of a 500-μm-long SiN waveguide, with adiabatic tapering of the width from 14 μm in the grating area to the standard 1 μm in the waveguide area. The SiN waveguides were fabricated by LIGENTEC using its proprietary process and cladded by oxide afterwards. After chemical-mechanical polishing, a-Si was deposited in-house using plasma-enhanced chemical vapor deposition and patterned using e-beam lithography followed by a chemical dry etch. Finally, the chip was coated with Polymethylmethacrylate (PMMA) as a cladding.

3. Discussion and Optimization

The suggested coupler scheme is fabrication tolerant. Fig. 2(a) shows the sensitivity of the CE at 1550 nm as a function of the a-Si and ILO thickness. The grating has a 1-dB sensitivity of over 100 nm for the a-Si thickness and of over 150 nm for the ILO thickness, respectively, suggesting an extraordinarily high fabrication tolerance for our device.

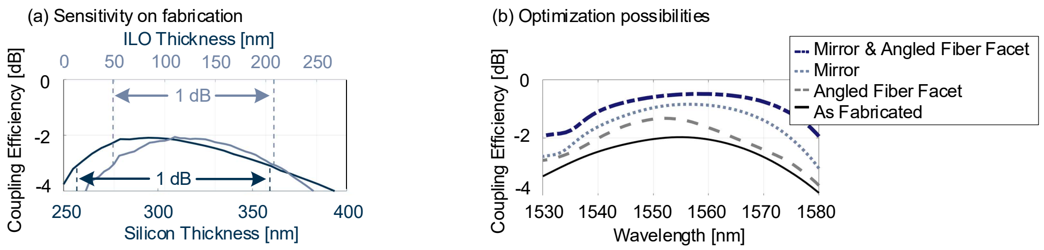

Fig. 2. (a) Sensitivity of the CE with variations in a-Si and ILO thickness. (b) Optimization possibilities reduzing coupling loss to 1.33 dB with an angled fiber facet (gray dashed), to 0.9 dB with a metal mirror (blue dotted) and to 0.5 dB when both are combined (blue dash dotted). No further changes to the grating parameters as fabricated (black solid line) have been applied.

The grating can be further improved by advanced techniques, see Fig. 2(b). Simulations show that replacing the standard single-mode fiber by a polished fiber with an angled facet of 4.5° increases the CE to -1.33 dB (dotted line). Further, by adding a metal mirror below the buried oxide layer, one could collect the back reflections and improve the CE by over 1 dB (dashed line). The combination of the two methods yields an astonishing CE of -0.5 dB as supported by 2D FDTD simulations (dash-dotted line). The 1-dB bandwidth extends over more than 35 nm. All the improved CEs were obtained without adapting the parameters as introduced in the fabricated grating.

4. Summary

A highly efficient grating coupler offering large fabrication tolerance has been presented for the ultra-low-loss SiN platform.We demonstrate a CE of -2 dB (sim.) and -2.7 dB (meas.) for a TE mode in the C-Band. Furthermore, we investigated the potential of the technology to reduce losses to values in the order of 0.5 dB by introducing angled fibers and mirrors as enabled by back-end-of-the-line postprocessing steps. To this day, efficient grating couplers have been missing in the SiN toolbox. The suggested approach offers a simple and highly efficient solution to a pending issue and might help to further leverage the SiN technology platform.

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