Efficient Surface Normal Multi-Stage Grating Couplers in Silicon Based Waveguides

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***Abstract*—A multi-stage fiber-grating coupler design is evolved from random conditions, fabricated, and tested on a silicon platform. Simultaneous input/output coupling from a standard fiber array at perfectly normal incidence yields a 59.8% efficiency per grating.**

***Keywords*—Si Photonics; grating coupler; normal incidence; genetic algorithm**

I. INTRODUCTION

Coupling light from optical fibers to silicon-based waveguides remains a nontrivial task due to their extreme mode profile mismatch. Fiber-to-waveguide grating couplers have arisen over the past decade which nearly match the mode profile of a fiber, resulting in broadband, efficient, and translationally tolerant coupling when the fibers are nearly normal to the chip surface [1]. This coupling approach eliminates the expensive need for optically smooth chip edges in traditional end-fire coupling, but a new restriction takes its place: Fibers must be angularly detuned from surface normal coupling in order to suppress counter-propagating and substrate-bound modes [2]. Although eliminating fiber tilt would decrease packaging costs, increase mechanical robustness, and augment the mass-marketability of optically interconnected semiconductor chips, successful efforts have either required extreme fabrication complexity [3], an extensive bottom reflector [4], extra high resolution fabrication steps [5], or significant expansion of the device's footprint by simultaneously coupling to two counter-propagating waveguides [6].

In addition, grating couplers are usually designed solely from first-principles with a single period and fill factor, effectively eliminating two of the most significant degrees of freedom available to a designer. To circumvent the difficulty of relaxing first-principle design, previous works have employed a genetic algorithm to slightly vary a traditionally designed grating in order to obtain marginal efficiency increases [3, 5, 7]. However, departing from an initial first-principle design could manifest new structures that enable high performance coupling across many platforms, specifications, and fabrication constraints.

In this work, a fiber-grating coupler is evolved from a genetic algorithm without starting from first-principle design. In order to demonstrate the flexibility of this approach, the grating is constrained to surface normal coupling and is experimentally reduced to practice in a single lithography step on a silicon platform. After re-employing genetic optimization to mitigate fabrication tolerances, input and output fibers from a fiber array are simultaneously coupled to and from the final optical circuit.

II. DESIGN AND SIMULATION

In order to efficiently and maximally explore the potential design space for a fiber-grating coupler, an in-house genetic algorithm was created. The grating design consists of a string of numbers, where each number represents the variable period or fill factor of a particular grating cell. Variable etch depth for each cell was also originally represented, but this was later fixed to 60% of film depth for all cells, as this drastically simplified fabrication without significantly compromising the end result. By partially etching the film, grating emission more constructively interferes toward the fiber and suppresses undesirable emission toward the substrate. The bottom oxide thickness was also optimized and fixed to 2.38 μm, which maximized upward emission in preliminary FDTD simulations.

Number strings of grating periods and fill factors were then compared, and strings with the highest coupling efficiency exchanged some of their values. Occasionally, values are also randomly changed during this exchange. This entire process creates new grating designs that retain similarities to previous designs. Another iteration occurs by comparing these new designs and swapping number strings of the best designs. This approach, known as a genetic algorithm, can reach the global optimum of a problem space, but a very large number of iterations are usually required to reach it, and each iteration simulates tens of new grating designs. Thus, an eigenmode expansion and propagation tool, CAMFR, was utilized due to its accuracy and extreme speed in simulating small-featured 2D profiles [8]. Overlap integrals between a grating field emission and a vertical fiber yielded the "fitness" (coupling efficiency) for each grating.

When starting with a first-principle, surface normal, grating coupler design where the grating period $\Lambda=\lambda/n_{eff}$ and fill factor was 50% for all grating cells, the genetic algorithm quickly saturated at 40% coupling efficiency with minimal changes to the starting design. Next, the genetic algorithm was restarted with purely random designs, and after approximately 200,000 simulations, the genetic algorithm plateaued with a 68% coupling efficiency, as shown in Fig. 1. In this design,

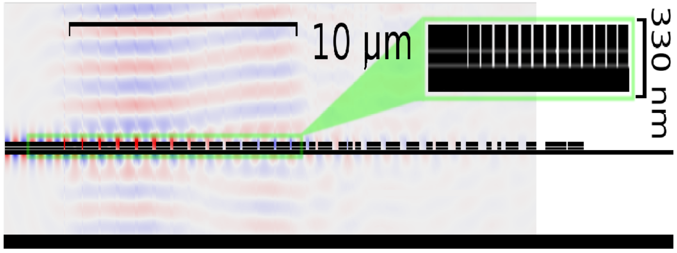

Fig. 1. Grating cross section showing simulated surface normal emission to a fiber aperture from a waveguide on the left. Silicon is shown in black. The green inset shows an enlarged view of the emitting/receiving portion of the grating. The etch depth for all sections is 200 nm.

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the first few grating teeth are apodized to impedance match the waveguide. The next stage is chirped to maintain normal emission. These effects linearly ramp the phase front, which is compensated by a shorter grating period in the third grating stage. The final 12 µm long stage partially emits but mostly reflects the remaining 17% of light into the third stage with varying phase offsets that depend on how deeply the light penetrates the reflector, which further flattens the tail of the emitted phase front through destructive interference.

III. FABRICATION AND RE-DESIGN

Details regarding the layers deposited in our particular SOI platform have been covered in previous works [9, 10]. Ellipsometry of the samples confirmed a slight over-deposit of 10 nm, resulting in a lower theoretical efficiency of 50%. 2,000 additional iterations of the genetic algorithm with the true film thickness re-obtained 68% efficiency with very minor design modifications. The design was then patterned in ZEP-520A resist by a 50 kV JEOL 6000 electron beam system, which stochastically introduced 3 +/- 20 nm of width and translation error per grating cell, lowering the theoretical efficiency to 55%. Feeding this error source into the genetic algorithm and re-evolving the design over 5,000 iterations resulted in a new theoretical efficiency of 63% that was robust against minor lithography errors. After patterning this new design, the device was completed with a single cycle of reactive-ion-etching which created both partially-etched gratings and their connected rib waveguides. A top-down SEM of the grating's four operating regions is shown in Fig. 2.

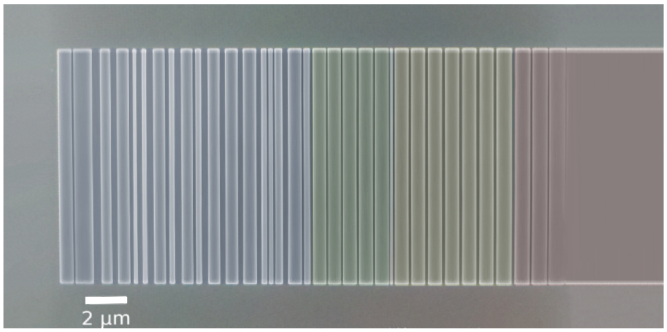

Fig. 2. Colorized SEM depicting each grating stage. Red is the apodized grating/waveguide interface, yellow is the primary fiber-coupling region, green is the secondary coupling region of shorter grating period, and blue is the quasiperiodic DBR to reflect light back into previous grating stages.

IV. RESULTS AND ANALYSIS

Although the grating was initially designed for TE polarization, the design in this work operates with TM polarized light to mitigate scattering from high side-wall roughness (~20 nm). Thus, TM polarized light from an EDFA broadband source was fed into a polarization-maintaining fiber array mounted to a 6-axis stage, which then positioned the array directly above the grating couplers as shown in Fig. 3. The output was fed into an optical spectrum analyzer, shown in Fig. 4, yielding a peak efficiency of 59.8% at 1555.8 nm. Signal was maximized when the fiber array was perfectly normal to the surface. The shift from the designed 1550 nm peak is due to overcompensating e-beam width errors in the new design, as tooth width variance exceeded trench variance, increasing the grating's propagation constant, weakening the grating, and shifting emission to longer wavelengths. The fiber array contains ~0.3 µm of translational misalignment between its fibers, which accounts for the 3.2% lower peak efficiency.

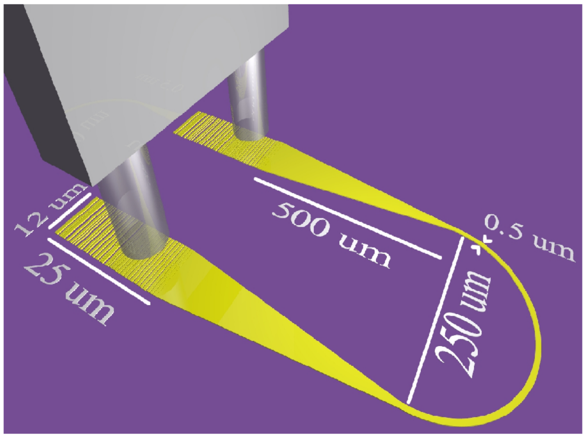

Fig. 3. Illustrated chip layout coupled to a normally-incident input/output fiber array. The grating-coupled waveguides are adiabatically tapered to single mode propagation before experiencing a circular 125 µm radius U-turn .

Fig. 4. Spectrum of single mode fiber coupling efficiency for a single grating.

V. CONCLUSION

In conclusion, a four stage input/output grating coupler of 68% theoretical efficiency was designed via a genetic algorithm without using first-principle design. It was then fabricated in a single lithography step and measured from a single mode fiber array at perfectly normal incidence, yielding an experimental coupling efficiency of 59.8%.

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