Increasing the Grating Coupler Bandwidth with a High Numerical-Aperture Fiber

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Abstract— **We propose and demonstrate that a small core high numerical-aperture single mode fiber will increase the coupling bandwidth of a silicon waveguide grating coupler. Without modifying the grating coupler design, the 1-dB coupling bandwidth was increase by ~60% to 53nm without significant coupling efficiency degradation.**

I. INTRODUCTION

The emerging potential applications of optical interconnects for energy efficient on-chip global interconnects and high bandwidth processor to memory applications require efficient coupling of light between silicon chip and optical fibers. Broadband coupling with high coupling efficiency is particularly desired for wavelength division multiplexed network on chips. Waveguide grating couplers provide an attractive solution to couple light in and out of the silicon chip as they do not constrain the position of the input/output to the edge of the chip. Various grating coupler designs have been proposed and investigated to overcome the high intrinsic loss due to the mode size mismatch between the optical fiber and the compact silicon waveguide [1-5]. However, most of these efficient grating couplers designs do not have wide coupling bandwidth. To improve the coupling efficiency, a large effective index of the grating region is required to achieve large coupling strength, but this would reduce the coupling bandwidth [6]. In order to extend the bandwidth, grating coupler designs based on silicon nitride [6], two-dimensional subwavelength structures [7], etc. have been proposed to reduce the effective index of the grating region. However, these approaches typically also reduce the coupling efficiency, and increase the device's complexity.

Basically, the fiber-chip coupling efficiency depends on the two basic elements, naming the grating coupler and the optical fiber. "Standard" single mode fibers (SSMF) are conventionally not considered as a design constraint, and attention was placed on extending the bandwidth by redesigning the grating coupler. However, in this article, we demonstrate that, by using a commercially available small core high-numerical-aperture fiber (HNAF) that was designed to reduce splice loss between small core erbium doped fiber and standard single mode fiber, we can improve the coupling bandwidth without degrading the coupling efficiency. No modification of the waveguide coupler design is required. Around ~50% relative increase in the 1-dB coupling bandwidth has been shown by both numerical simulation and experiments. Besides, by optimizing the fill factor, a 1-dB bandwidth of 73 nm is predicted by simulation.

II. SIMULATION RESULTS

We have performed two-dimensional finite-difference-time-domain (2D FDTD) simulation to study the performance of the grating coupler. A grating coupler fabricated with 250-nm thick silicon layer SOI wafer was considered. The etch depth was set to be 80 nm, while the grating period was 600 nm. The fiber was tilted 10° with respect to the grating surface normal. The HNAF has a mode-field-diameter (MFD) of 4.2 μm at 1550 nm, while the MFD for a SSMF was 10.4 μm. At different fill factors (*fx* =0.4, 0.5, 0.6), the coupling spectra of both SSMF and HNAF have been plotted in Fig. 1. It can be seen that the HNAF could always maintain a slower envelope decrease at different fill factors, thus producing a larger coupling bandwidth. Despite the increase in bandwidth, the peak coupling wavelength and the maximum coupling efficiency, for both SSMF coupling and HNAF coupling, were always similar at different fill factor cases. This implied that, by replacing the SSMF with the HNAF, the phase matching condition for peak coupling process would not degraded significantly to obtain a larger bandwidth.

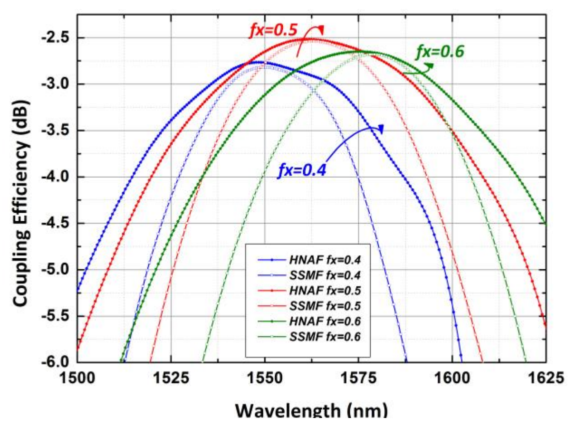

Fig. 1. 2D FDTD simulation results of coupling spectrum at three fill factors for SSMF and HNAF

The increase in bandwidth could also be understood by considering the phase matching condition for waveguide grating coupler:

$$n_{eff} \cdot \frac{2\pi}{\lambda} = n_0 \cdot \frac{2\pi}{\lambda} \cdot sin\theta_0 + q \cdot \frac{2\pi}{\Lambda} \quad (1)$$

At the center wavelength (λ_0), the diffraction angle (θ_0) could be determined from this equation. This diffraction angle was the fiber tilt angle in both simulations and experiments. However, other than the center wavelength, this equation would not be strictly satisfied at the fixed tilt angle θ_0 and thus would result in variations in the diffraction angle for light with different wavelengths, which is related to the drop in their coupling efficiency. The HNAF usually has a smaller fiber core radius, which corresponds to a smaller beam waist. It has a larger acceptance angle at the fiber-air interface, thus it is less sensitive to the variation in the diffraction angle, as compared with the larger SSMF. As a result, the coupling efficiency would not drop too much at the wavelength region slightly deviated away from the center wavelength, leading to much broadened bandwidth. The detailed 1-dB coupling bandwidth values and relative comparisons for SSMF and HNAF coupling at three fill factors have been listed in Table 1. By using the HNAF, relative increase in 1-dB coupling bandwidth of ~47.7%, 46%, 50% were obtained at *fx* =0.4, 0.5, 0.6, respectively.

TABLE I. SIMULATION RESULTS OF 1-DB COUPLING BANDWIDTH

Fill Factor	1-dB Coupling Bandwidth		
	SSMF	*HNAF*	*Relative Increase*
0.4	44 nm	65 nm	~47.7%
0.5	50 nm	73 nm	46%
0.6	48 nm	72 nm	50%

III. EXPERIMENTAL RESULTS

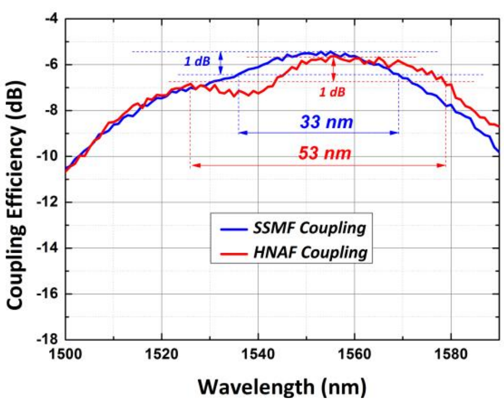

Fig. 2. Experimental results of the coupling spectrum for SSMF and HNAF with a same grating coupler

Based on the previous analysis, the designed grating coupler was fabricated on a silicon on insulator wafer whose silicon layer and buried oxide layer thickness were 250 nm and 3 μm, respectively. The etch depth of the grating etching region was 80 nm, the grating period was 600 nm and the fill factor was chosen to be 0.5. Two 400 μm-long tapers were used to guide the on-chip mode between the input/output 12-μm-wide grating coupler and a 10-μm-long silicon nanowire with 500 nm×250 nm cross section. In order to characterize the bandwidth performance, a pair of HNAFs (THORLABS, NA=0.35, SiO_2/GeO_2 UHNA3 fiber). In the control experiment, a pair of SSMFs was used. For each case, the fiber was fixed at 10° tilt angle with respect to the input/output grating coupler surface normal direction. Fig. 2 shows the experimental results. By using HNAF, a 1-dB coupling bandwidth of 53 nm was obtained, which was 20 nm larger than that of the case of using SSMF. This corresponded to about ~60% relative increase in the coupling bandwidth. Meanwhile, the peak coupling efficiency shows no much difference. It is noteworthy that we use a 12 μm-wide grating coupler for characterization, which is much larger than the 4.2 μm MFD of HNAF. However, due to the large numerical aperture of HNAF, the light beam will have a large diffraction angle after going into free space from the fiber. This diffraction angle increase helps keep a nearly constant beam size at the upper surface of the grating region as the SMF case. And this explains why the coupling efficiency will not be changed significantly after employing HNAF which has a much smaller fiber core. The discrepancies (2.7 dB maximum) between the experimental results and the simulation results could be attributed to the possible fabrication error, as the fill factor has not been precisely controlled. This could be alleviated via better fabrication and more precise control in the polarization states.

SUMMARY

Based on the analysis of waveguide grating coupling bandwidth dependence on diffraction angle variation, we employed HNAF, instead of SSMF, to decrease the angle variation sensitivity and broaden the coupling bandwidth. A 1-dB coupling bandwidth of 53 nm (~60% relative increase) was experimentally observed without degrading the coupling efficiency, nor changing the grating coupler design. This work provides an effective solution to enhance the performance of broadband fiber-to-chip coupling and could potentially benefit the broadband on-chip applications, such as optical interconnects, etc.

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