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Low connector-to-connector loss through silicon photonic chips using ultra-low loss splicing of SMF-28 to high numerical aperture fibers

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Abstract: Here we present extremely low connector-to-connector loss (≤3 dB) through silicon photonic chips using ultra-low loss (≤0.15 dB) splicing between SMF-28 and ultra-high numerical aperture (UHNA) fibers. The small MFD from the UHNA fibers enables strong coupling to hybrid TE/TM edge couplers achieving TM (TE) losses of 1.25 (2.35) dB per coupler and low polarization-dependent loss. Mode coupling simulations and tolerance are investigated to understand performance.

1. Introduction

Data transmission is a critical infrastructure source that has become increasingly reliant on fiber optic technology to help it achieve large bandwidths at lower power consumption. For the past three decades significant efforts have led to the development of low-loss optical fibers getting down to <0.2 dB/km making the chip coupling efficiency a significant bottleneck [1].

Fiber-to-chip edge coupling in photonic integrated circuits has been an ongoing challenge due to the mode mismatch between SMF-28 and Silicon waveguides. In general, two approaches have been taken: (1) the use of complex on-chip mode converters which require the removal of the Silicon substrate in order to properly match to the large SMF28 mode [2,3]; or (2) lensed fibers to decrease the mode field diameter (MFD) to better mode match directly to a Silicon-on-Insulator waveguide coupler. However, these solutions come at a high cost either due to complicated chip processing or production of lensed fibers which also are challenging to precisely align the chip at the lens's focal spot. In contrast, some optical fiber manufacturers produce low-cost optical fibers with an ultra high numerical aperture (UHNA). These UHNA fibers have an inherently small MFD (~3-5um) that is well matched to most Silicon waveguide edge couplers and can be directly butted against the edge of the chip, simplifying alignment and packaging. However, until now, this had limited utility due to the challenge of transitioning from the high-NA fiber mode to SMF-28 external components.

Here we present ultra low splicing loss (≤0.15 dB) between SMF-28 and four different types of UHNA fiber with varying MFD's suitable for coupling to silicon photonic chips. Furthermore, using these spliced UHNA fibers we demonstrate very low connector-to-connector (CtoC) (tunable laser to photodetector) loss (≤3dB) and polarization dependent loss (PDL) (TE mode transmission - TM mode transmission) through an AIM Photonics chip using the AIM Process Design Kit (PDK) [4] edge couplers. This article is divided up as follows: in section 2) we detail

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the splicing technique and present data with respect to its repeatability and in 3) we detail the fiber-chip coupling measurements and compare to simulations of the tailored edge couplers.

2. SMF-28-to-UHNA Splicing

Several approaches have been proposed to improve splicing results by tapering [5], thermal expansion [6] and bridging [7], or a combination of these methods [8]. Fiber bridging (where multiple fibers are sequentially spliced together to incrementally reduce the MFD) is widely used to splice to fibers with small MFD's but each bridge splice introduces loss (scattering and reflections), decreases the overall reliability and is costly.

In our approach, we directly splice from SMF-28 to Nufern's UHNA fibers with very low loss. UHNA has a specially Germanium-doped core that thermally expands during fusion splicing, creating a taper to meet the MFD of SMF-28 back down to the original MFD of the UHNA. A filament fusion splicer was utilized (Vytran FFS2000WS) due to it's ability to control the thermal profile of the splice and fire polish [9]. In order to ensure sufficient thermal expansion we optimized the splicing process and found that the splicing duration, power, and fire polishing power are the major factors which affect the splice loss. Furthermore, the power delivery of the tungsten filament is normalized every two-hundred seconds of usage to ensure that the splicing remains reproducible.

Preparation of fibers for the first set of measurements was carried out by splicing UHNA fibers to SMF-28 with an arc duration and power unique to each fiber (Table 1). The long duration gives the doped ions time to diffuse and expand the core leading to an adiabatic matching between cores [10]. The variation in arc duration is likely related to the composition of the fiber cores. These parameters were obtained through a systematic study over many splicing experiments and were found to have a nominal variation depending on the brand of starting SMF-28 patch cable. After the splice was completed, a low index (n=1.55) acrylic layer (AngstromBond DSM 950-200) was applied to reinforce and strengthen the splice joint.

Table 1. Optical fiber characteristics and UHNA-SMF28 splicing performance measured at 1550 nm. Splicing loss was determined by power transmitted from laser to detector via SMF-28 fiber compared to laser to detector via spliced fiber. Splicing recipe (arc duration and power) values are included which yields optimal splice loss for each fiber.

SMF-28 to *	MFD (μm)	Core NA.	Single Splice Loss (dB)	Arc Duration (s)	Power (W)
SMF-28	10.4	0.14	0.04	5	21
UHNA1	4.8±0.3	0.28	0.08	12	21
UHNA3	4.1±0.3	0.35	0.12	12	20
UHNA4	4.0±0.3	0.35	0.06	16	21
UHNA7	3.2±0.3	0.41	0.03	25	21

We obtained a splice loss of less than 0.15 dB between standard SMF-28 to four types of UHNA fibers each with a different sized MFD (Table 1). The splice loss was measured by splicing together a patch cable with two mode conversions (SMF28-UHNA-SMF28), and then measuring the transmission. The transmission was normalized to an identically connectorized reference SMF-28 fiber. As seen in Fig. 1(a) the transmission was greater than −0.3 dB for all of the fibers across the entire bandwidth of our tunable laser (Keysight 8164B Lightwave Measurement System). Consequently, the loss of each splice can be inferred to be less than 0.15 dB by assuming uniformity in the two connections.

We verified the repeatability of our recipe by assembling 10, SMF-28-UHNA7-SMF-28 patch cables and measuring their power losses. The distribution of losses from the fiber cables is presented in Fig. 1(b) featuring an almost loss-less transmission. We attribute the nominal losses to fiber connector misalignment.

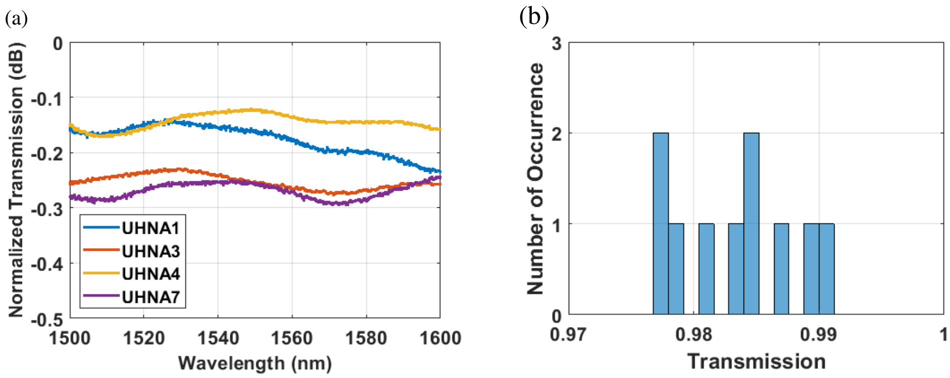

Fig. 1. (a) Normalized transmitted power of SMF-28 spliced to UHNA spliced to SMF-28 optical fiber. Another SMF-28 fiber was used as a reference to determine the loss. (b) Percent of transmitted power from a set of SMF28-UHNA7 optical fiber patch cables.

3. Fiber to chip measurements

Figure 2(a) shows the schematic of the fiber to chip coupling setup. An input fiber is positioned normal to the edge coupler facet with a piezo-driven stage that can scan the fiber position in both the y- and z-direction with a 20 nm resolution. The optical power is coupled on and off the chip using two identical edge couplers and recorded by an off-chip power meter. The total loss of the fiber-chip-fiber connection can be extracted by calibrating out the measurement system loss, and the coupling efficiency of a single edge coupler is, therefore, half of the total loss. In silicon photonics, the edge coupler serves to expand the strongly confined waveguide mode in the photonic circuit to match the fiber mode. The origin of the coupling loss, therefore, consists of two parts: (1) the mode mismatch between the edge coupler and the fiber and (2) the mode size transition loss from the edge coupler to the waveguide. To facilitate fiber selection and fiber-to-chip packaging, AIM Photonics [4,11] provides an accurate model that takes into account both origins of loss to determine the coupling efficiency and alignment tolerance of a TE/TM edge coupler in its PDK library.

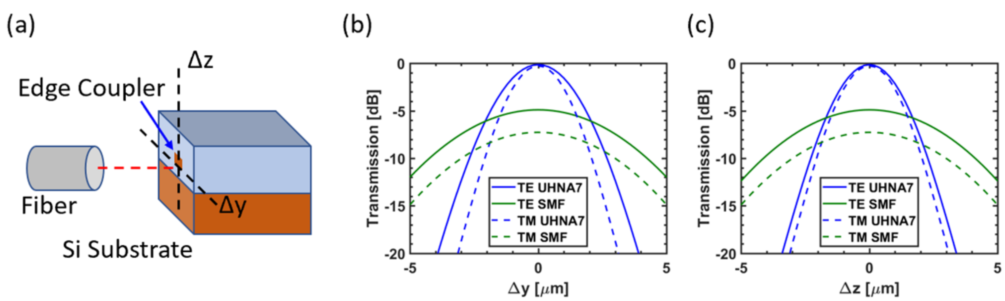

Fig. 2. Schematic of the fiber-to-edge coupler testing setup. Mode overlapping calculation of the AIM PDK TE/TM Edge Coupler to SMF28 and UHNA7 fibers offset in (b) y- and (c) z-direction. The transmission peaks at Δy=Δz=0 and starts to roll-off when the fibers are out of alignment from the maximum coupling position. Solid and dashed line represent TE and TM mode overlap, respectively. All calculations used a 1550 nm source.

The TE/TM edge coupler provided by AIM Photonics through the multi-project wafer (MPW) run is designed for small-core fibers that can couple both TE and TM polarized light with high efficiency. The edge couplers were designed to support modes with an effective index that closely matches the SMF28 mode (n_{eff} = 1.45 ± 0.01)). The TE mode has an elliptic Gaussian profile with 1/e^2 diameter of 3.6 μm and 2.8 μm in the y- and z-directions, respectively. For the TM mode, the mode size is 2.4 μm and 2.3 μm in y- and z-direction, respectively. We calculate the mode overlaps between the edge coupler modes and the modes of both SMF28 and UHNA7 fibers, as shown in Figs. 2(b) and (c). The mismatch of the UHNA7 mode to the edge coupler TE (TM) modes results in 0.14 (0.27) dB per facet loss while the SMF28 fiber TE (TM) mode suffers a significant worse loss of 4.9 (7.3) dB per facet. Adding the transition loss for the SMF28 and UHNA7 fiber coupling, the total TE (TM) coupling loss for the UHNA7 fiber is 1.5 (1.0) dB per coupler while the TE (TM) coupling loss for SMF28 fiber is 5.5 (7.5) dB per coupler. Therefore, the polarization dependent losses (PDL) of the edge coupler for UHNA7 and SMF28 are 0.5 dB and 2 dB per coupler.

These simulation results line up quite nicely with experimental findings (Table 2). Specifically, UHNA4/7 realized less than 3dB Connector-to Connector [CtoC] loss for TM polarization and exhibited a low PDL of approximately 1dB. This low loss coupling is clearly seen in the spectral TE and TM transmission from laser to detector as seen in Figs. 3(a) and (b), respectively. Data shows both UHNA4 and UHNA7 have very high CtoC transmission, particularly for TM polarization which has a very low loss of 2.5 dB at 1550 nm.

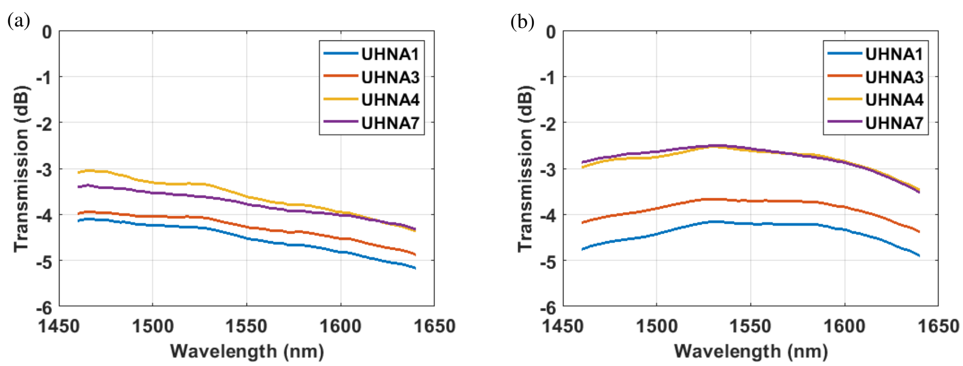

Fig. 3. Spectral dependence for the Connector-to-Connector transmission through an AIM photonic chip for: (a) TE mode and (b) TM mode using SMF28 spliced to UHNA optical fibers.

Table 2. Connector-to-Connector [CtoC] loss measured at 1550 nm. Loss is measured as power transmitted from laser to detector via SMF28 compared to transmission from laser through spliced fiber, to chip, to spliced fiber onto detector.

SMF-28 to *	CtoC TM Mode Loss (dB)	CtoC TE Mode Loss (dB)	PDL (dB)
SMF-28	N/A	>6	N/A
UHNA1	4.2	4.5	0.2
UHNA3	3.7	4.2	0.6
UHNA4	2.5	3.5	1.0
UHNA7	2.5	3.7	1.2

We also measured the alignment tolerance of the UHNA7 fiber coupling to the edge coupler. The 1 dB roll-off width is measured to be 1.4 (1.3) μm in Δy (Δz) direction for the TE-polarized input and 1.2 (1.2) μm in Δy (Δz) for the TM-polarized input, as shown in two-dimensional coupling loss mapping in Figs. 4(a) and (b). We used the provided mode size and calculated the alignment tolerance from the Gaussian profile model. The results are shown in Figs. 4(c) and (d), demonstrating a good agreement with the experimental results. The calculated 1 dB alignment tolerance for the SMF 28 fiber TE mode is 3.75 (3.65) μm in Δy (Δz) and 3.6 (3.6) μm in Δy (Δz) for TM mode. Horizontal and vertical cuts from Figs. 4(a-d) are shown in Figs. 4(e) and (f) and show good agreement between the experimental and simulated results. This proves that the model provided by AIM Photonics is accurate in representing characteristics of the edge coupler and demonstrates that the UHNA7 fiber can greatly improve the coupling loss to silicon photonics chips with a slight degradation in the alignment tolerance.

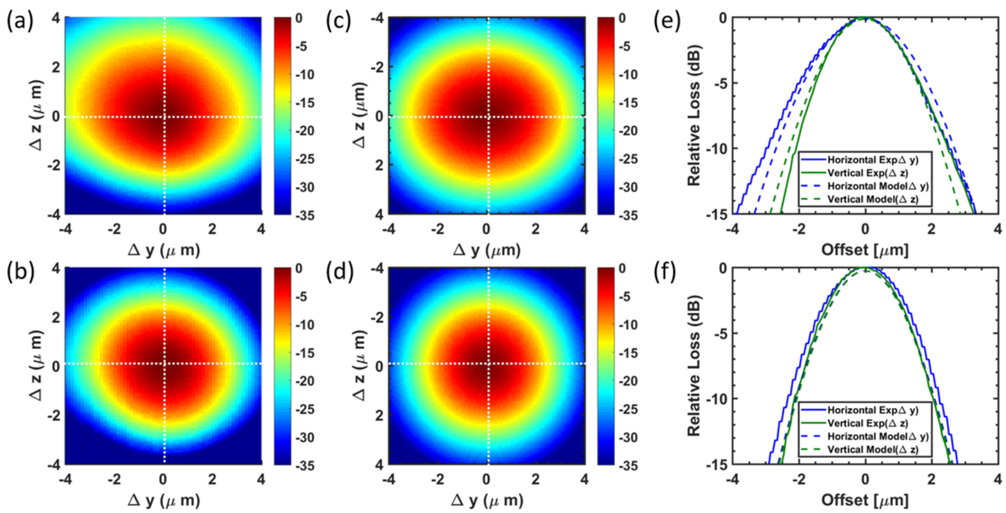

Fig. 4. Experiment results of the UHNA7 fiber alignment tolerance to the (a) TE, and (b) TM mode of the TE/TM edge coupler. Calculated alignment tolerance of the (c) TE and (d) TM modes based on the edge coupler model provided by AIM Photonics. (e) Horizontal (Δy) and vertical (Δz) cuts of the white dashed lines in (a) and (c). (f) Horizontal (Δy) and vertical (Δz) cuts of white dashed lines in (b) and (d).

4. Conclusion

We have developed very low loss splicing between SMF28 and UHNA fibers and used them to demonstrate low loss coupling to Silicon Photonic chips optimized for low PDL. We have also measured low loss C-band coupling and TE-only coupling using similar spliced fibers. We have found that the splicing is very repeatable. We will continue to optimize both the edge coupler design and the splicing recipes, particularly for other types of high-NA and specialty fibers. Lastly, we believe performance can be further improved by optimizing additional splicing parameters such as splicing gap, push-in velocity and push-in distance.

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