A Single-Mode Expanded Beam Separable Fiber Optic Interconnect for Silicon Photonics

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Abstract: An expanded beam optical interconnect is introduced that provides a separable connection between photonic integrated circuit and single-mode fiber. Insertion loss data are provided and stability through solder reflow is demonstrated.

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1. Introduction: The Need for Separability

The advent of silicon photonics devices containing integrated optical and electrical circuits has driven a wave of low-cost, single-mode transceiver formats in recent years. These transceiver links typically use permanently attached actively aligned optical fibers that are not separable from the photonic integrated circuit (PIC) device [1-4]. While these approaches support pluggable transceivers, they complicate and restrict the implementation of on-board optics or future Application Specific Integrated Circuit (ASIC) co-packaged devices with optics due to the handling and testing of the permanently attached fiber assemblies. The acceleration of link technology and power consumption is rapidly pushing the limits of physics with regard to electrical transmission on the host PCB from ASIC to electro-optical (EO) conversion. While permanently attached fiber on-board Tx/Rx modules are technically feasible, there is simply no viable path to a co-packaged silicon photonic device without a separable fiber optic connection.

2. Considerations for Optical Coupling into Silicon Waveguides

Separable fiber optic connections can be broken down into two basic categories: physical contact and expanded beam interconnects. Physical contact connections involve direct fiber contact either to a waveguide or grating coupler, whereas expanded beam connections involve optics that expand and collimate the beams without any physical contact between the fibers and the waveguide.

Coupling optical fibers through physical contact to silicon waveguides using a separable connection presents a series of challenges - the optical mode in the silicon waveguide must match the mode in optical fiber, and sub-micron level alignment between the components is required during attachment. Furthermore, physical contact connections require high forces to physically connect pre-polished fibers, and the connections are extremely sensitive to performance degradation due to the presence and/or generation of debris before or during the assembly process.

Expanded beam interconnects can help minimize the problems of debris, alignment sensitivity of the separable components and high mating forces between them. In addition, the reduction in mating forces for an expanded beam interface allow for the possibility of smaller form-factor connectors.

3. The Approach: A Separable Expanded Beam Interface

This paper introduces a low force separable interface between the silicon photonics package and the fibers. This technology couples the beam from a photonic grating coupler package to single-mode fiber via an expanded collimated beam. The connection is separable within the collimated space, as shown in Figure 1(a).

The complete transceiver path can best be conceptualized as having two independent components: the photonic integrated circuit (PIC) and the optical interconnect, with each capable of emitting and receiving a similar collimated beam. The PIC is comprised of the silicon waveguide devices, each with a grating coupler to direct the beam, and a micro-lens array (Figure 1(b)) at the grating coupler exit to create expanded collimated beams at 50 µm diameter. The micro-lens array is bonded within a pocket of a solder reflow compatible molded polymer receptacle to form the lens receptacle assembly prior to attachment to the PIC.

The optical interconnect is a monolithic molded single-mode fiber optic ferrule with a total internal reflection (TIR) lens inside the ferrule (Figure 1(b)), while aligns to the expanded and collimated beam from the PIC. The TIR lens in the ferrule changes the beam path by 90 degrees to the fiber axis, and couples the beam into the single-mode fiber that is captured in a micro-hole array in the ferrule. The ferrule contains mating features that couple to the lens receptacle assembly to align the PIC and interconnect across the expanded beam interface and form the separable connection.

Alignment of the lens receptacle assembly to the grating couplers on the PIC can be accomplished passively using pick and place equipment. Alternatively, the optical interconnect can be mated to the lens receptacle assembly and the pair can be actively aligned to the PIC. Active alignment provides the additional opportunity to compensate for some manufacturing tolerances of the system assumed in the Monte Carlo simulations discussed later and to achieve a higher coupling efficiency. The mechanical alignment between the PIC and interconnect at the separable connection is accomplished by a set of matching male/female “dog-bone” shaped alignment features on the ferrule and the receptacle that work similarly to the traditional pin/hole mating alignment. The female dog-bone feature is visible at the top of the receptacle in Figure 1(a) surrounding the fused silica lens array.

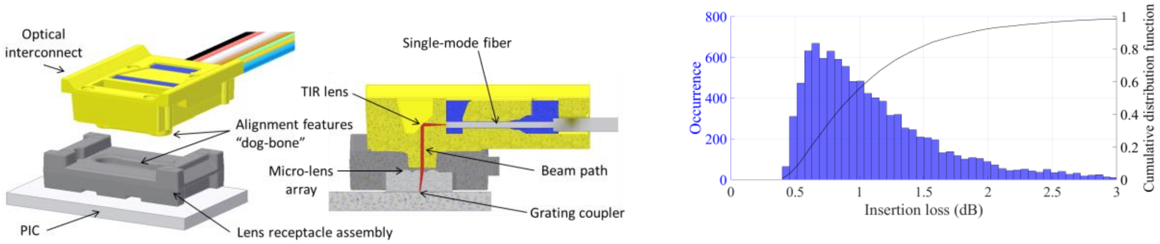

Figure 1. (a) Overview of the optical interconnect and lens receptacle assembly, (b) cross-section view of the beam path, and (c) Monte Carlo simulation of insertion loss performance assuming a perfect Gaussian mode from grating coupler.

The coupling efficiency of the transceiver is dependent on the ability of the grating coupler to emit a spot with a mode matched to the single-mode fiber used, as well as the interface optics to maintain that mode. Manufacturing, temperature, and wavelength variances affect the performance of the coupler and must be taken into account. Figure 1(c) shows the simulated Monte Carlo insertion loss performance for the system, which achieves 98% of insertion loss values below 2.8 dB assuming a perfect Gaussian launch from the grating coupler.

Lateral and angular alignments in the optical link are important considerations to both system performance and manufacturability. The lateral alignments of the grating coupler (GC) to the micro-lens and of the single-mode fiber to the TIR lens are similar and most critical to system performance, while the sensitivities to angular misalignments within these pairs are also similar but relatively insensitive. These intra-component sensitivities can be seen in Figure 2(a), fiber/GC-to-lens offset sensitivity, and Figure 2(b) fiber/GC-to-lens tilt sensitivity. Lateral and angular alignment sensitivities between the lens receptacle assembly and the optical interconnect components are shown in Figure 2(a), lens-to-lens offset sensitivity, and Figure 2(b), lens-to-lens tilt sensitivity. The trade-offs inherent to the expanded beam approach become clear with an expanded beam causing sensitivity to lateral misalignments to decrease while the sensitivity to angular misalignments increases. This design considers this trade-off and strikes a balance to create a reasonable approach.

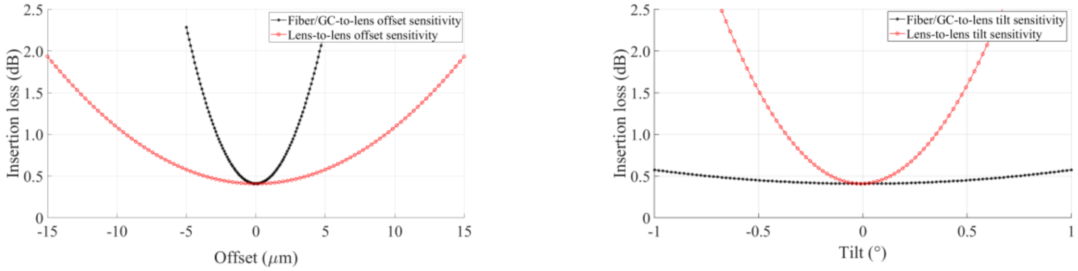

Figure 2. (a) Modeled lateral alignment sensitivity and (b) angular alignment sensitivity.

The use of the expanded collimated beam between the PIC device (CTE ~4 ppm/°C) and optical interconnect (CTE 50 ppm/°C) enables stable single-mode coupling by minimizing the effects of thermal expansion mismatch and lateral misalignment between the two lens arrays at the manageable expense of increased angular alignment sensitivity.

4. Testing Methodology and Results

The ability to independently verify the performance of the components is critical to development and large-scale production; both the PIC and optical interconnect can be tested independently prior to installation in the final system. Testing of the optical interconnect is accomplished independently from the PIC with the use of an interposer that allows an interconnect to be mated to a known reference interconnect to measure insertion loss performance using conventional fiber optic test equipment. The interposer fixture consists of a plate that aligns the reference interconnect to device under test, and applies a controlled mating force to hold both ferrules together during testing. Since the launch conditions of the reference interconnect are not identical to the Gaussian grating coupler launch (Figure 1(c)), there is an offset between the measured interposer insertion loss (Figure 3) and the expected system performance loss. However, the Monte Carlo simulation of interposer testing shown in Figure 3(a) demonstrates that interposer testing is sensitive to device performance and pass/fail criteria could be established for final system performance. Figure 3(b) shows the empirical results of 684 interposer tests on terminated optical interconnect assemblies.

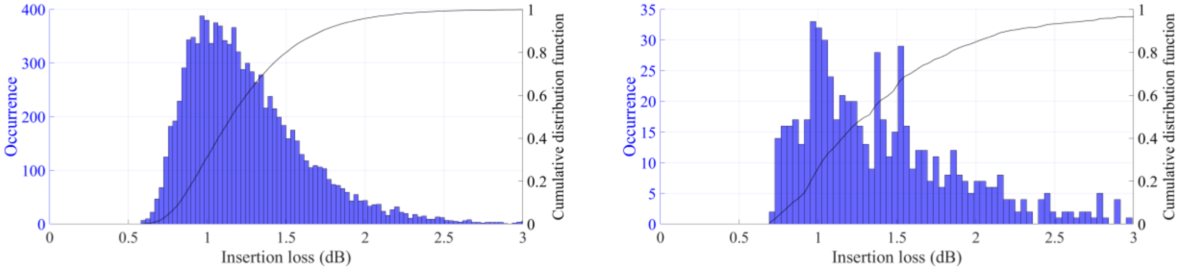

Figure 3. (a) Interposer Monte Carlo simulation, and (b) empirical results.

5. Solder Reflow Compatibility

The lens receptacle assembly needs to be stable through solder reflow conditions, if applicable, after it is aligned to the grating coupler. In order to demonstrate the component stability, the lens position was measured with respect to the dog-bone alignment features immediately after assembly. Parts were then cycled through a typical solder reflow process three times, and the parts remeasured. Table 1 shows the initial misalignment between the lens location and the dog-bone feature after assembly, and then the change in alignment after the three reflow cycles, demonstrating the lens receptacle assembly is stable through the solder reflow process.

Table 1. Stability of the lens and dog-bone alignment feature after solder reflow.

	Lens Position (microns)			
	As Built		**Shift - Post Reflow (3X)**	
	X	**Y**	**X**	**Y**
Average	-2.1	1.9	-0.3	-1.1
Range	7.8	-8.5	0.6	1.9

6. Summary

This paper demonstrates an optical interconnect that couples light between photonic integrated circuits and single-mode optical fiber via a separable expanded beam connection. Separability of the components reduces the alignment and assembling requirements compared to traditional direct coupling methods. Insertion loss data presented from 684 discrete measurements matches the theoretical Monte Carlo model. The components have been demonstrated to withstand multiple consecutive solder reflow cycles.

7. References

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