Novel, high-throughput, fiber-to-chip assembly employing only off-the-shelf components

Nicolas Boyer1, Alexander Janta-Polczynski1, Jean-François Morissette1,2, Stephan Martel1, Ted W. Lichoulas3, Swetha Kamlapurkar4, Sebastian Engelmann4, Paul Fortier1 and Tymon Barwicz4

1IBM Bromont, 23 Boul. de l’Aéroport, Bromont, Qc Canada
2Université de Sherbrook 2500 Bld. de l’Université, Sherbrooke, Qc Canada
3AFL Telecommunications, 170 Ridgeview Circle, Ducan, SC 29334 USA
4IBM T.J. Watson Research Center, 1101 Kitchawan Rd, Yorktown Heights, NY USA

Abstract—Cost-efficient assembly of single-mode fibers to silicon chips is a significant challenge for large-scale deployment of Si photonics. We have previously demonstrated a fully automated approach to parallelized assembly of fiber arrays to nanophotonic chips meant to be performed with standard high-throughput microelectronic tooling. Our original approach required a customization of a standard fiber component, which could limit cost-efficiency and scalability. Here, we demonstrate a novel approach to fiber assembly employing off-the-shelf fiber components only. The new concept employs a dual vacuum pick-tip that can be integrated in standard high-throughput microelectronic tooling. We validate this approach with assemblies of standard 12-fiber interfaces to nanophotonic chips. The assembly performance is assessed via x-ray tomography cross-sections, polished mechanical cross-sections, and optical coupling measurements.

Keywords—silicon; photonic; high-throughput; fiber; self-alignment; V-groove

I. INTRODUCTION

Silicon photonics leverages the microelectronic wafer fabrication infrastructure to create photonic circuits with unprecedented complexity and cost-efficiency. Legacy approaches to optical packaging rely on manual assembly or custom automation and do not match the cost efficiency and scalability of the wafer fabrication process. To fulfill the potential of silicon photonics, novel packaging approaches are required.

We have recently demonstrated a parallelized optical fiber-to-chip assembly compatible with standard high-throughput microelectronic assembly lines [1]. Our strategy has been to leverage existing microelectronic packaging facilities in order to match the scalability and cost efficiency of microelectronic foundries already used for photonic chip fabrication [2]. Our original concept is shown in figure 1. It starts with a fiber stub formed of a standard fiber interface at one end and an array of bare fibers at the other. A polymer lid is pre-attached on the bare fiber side and is used to pick and place the fiber stub on a matching V-groove array defined on the photonic chip. An angled sliding plane, on which the chip resides, trigonometrically transforms part of the vertical assembly force into a fiber sliding force for in-plane butting of fiber tips on waveguide couplers. The result is a three dimensional self-alignment of fibers to waveguides with sufficient accuracy for low-loss single-mode optical connections despite the lower placement accuracy of high-throughput tools.

The Achilles’ heel of our original approach is that it requires a modification to a standard fiber component, potentially limiting cost-efficiency and scalability. The fiber stub is standard but the addition of the polymer lid is a custom process which, even at high volume, would likely be done manually as most processes are in the fiber industry. In this paper, we address this shortcoming by experimentally demonstrating a novel approach to parallelized fiber-to-chip assembly employing only off-the-shelf components for best cost-efficiency and scalability. This new concept uses a dual vacuum pick-tip that can be integrated in standard high-throughput microelectronic tools. It is demonstrated here with off-the-shelf 12-fiber components assembled to V-groove arrays integrated on chip.

In our original approach, the pre-assembled lid was believed to be required for (1) ensuring that fibers in the array remain within the re-alignment range of the V-grooves on chip and (2) enabling handling of the stub by the fiber tips to apply assembly pressure directly on the fiber to V-groove interface to warrant correct fiber seating in V-grooves.

Since these initial assumptions, we have acquired statistics showing that fiber stubs with short bare fiber segments had more accurate fiber position in practice than expected from manufacturer specifications. As will be shown in section III below, we now believe that a pre-assembled lid is not mandatory for incoming fibers to be positioned within the re-alignment range of the V-groove array on chip.

For proper fiber seating in V-grooves, pressure still needs to be applied at the fiber to V-groove interface area. This cannot be done by direct contact between the pick-tip and the bare fibers as the UV adhesive used to fix the fibers in the grooves will contaminate the pick-tip and adhesively connect it to the chip during UV tacking. Hence, a buffer between the adhesive and the pick-tip is required. Any UV-transparent film can be used for this purpose and can be handled separately from the off-the-shelf fiber component with a dual pick-tip as described in section II below.

This novel approach was experimentally validated by assembling off-the-shelf 12-fiber connector components to V-groove arrays integrated on nanophotonic chips. The
performance is assessed in section IV below with cross-sectional analyses and optical coupling measurements.

II. NOVEL ASSEMBLY CONCEPT FOR OFF-THE-SHELF COMPONENTS

As schematically shown in figure 2, the novel assembly process demonstrated here uses only off-the-shelf components to optically connect fiber arrays to a nanophotonic chip using standard high-throughput pick and place equipment. The nanophotonic chip is designed with an array of built-in V-grooves to provide accurate three-dimensional self-alignment of the fibers to embedded waveguide couplers. A dual vacuum pick-tip is used to control the handling of the optical component and of a buffer independently.

The commercially available single-mode fiber stubs used here are formed of a twelve-fiber ribbon, stripped and cleaved on one side, and terminated with a standard MT fiber ferrule on the other side for interfacing to fiber connectors. A buffer is used to prevent the contamination of the pick-tip from the UV-curable adhesive used to mechanically bond the fibers to the silicon chip. This buffer is made of a UV-transparent material to allow curing of the UV adhesive beneath it. Our current work uses a polymeric buffer.

As shown in figure 2(a), the fiber stubs and the polymer buffers are fed separately on the tool. Three fiber stubs are represented on a receiving tray. The incoming buffers are presented on a waffle pack. Direct pick on sheets, dicing tapes or delivery in a tape and reel format could be another cost-effective alternative on a high-volume production platform.

The dual vacuum pick-tip, presented in figure 2(b), exhibits two independently controlled vacuum ports for the ferrule and buffer picking. The pick-tip should be made out of UV-transparent material in the buffer handling region to allow UV exposure of the assembly adhesive through the pick-tip. The height of the ferrule handling surface relative to the buffer handling surface must be adjusted to account for the ferrule geometry and the buffer thickness. Also, the pick-tip can be designed so that the distance between the two handling areas can be adjusted to accommodate various fiber stub geometries.

The buffer is first picked by activating the buffer vacuum port, as shown in figure 2(c). Generally speaking, the exact positioning of the buffer is not critical. Vision alignment is then performed on the ferrule of the fiber stub which is then picked by activating the ferrule vacuum port (figure 2(d)). The ferrule picking must be sufficiently precise to ensure that the fiber tips are well centered under the pick-tip and the buffer. One must be careful with ferrule picking angular inaccuracies due to the distance between the ferrule and the fiber tip. At this point, the buffer is maintained by the pick-tip and is simply resting above the bare fiber portion of the fiber stub.

The fiber stub and the buffer are then moved to the assembly location. There, the nanophotonic chip is vacuum held on an angled sliding plane. The fibers are coarsely aligned with vision to within ±10 μm relative to the V-grooves. This placement accuracy is commonly achievable on high-throughput pick and place tools found in most microelectronic assembly lines. The fibers are also aligned to land at a safe distance from the waveguide couplers terminating the V-grooves.

As the pick-tip is activated downward, the buffer makes contact with the bare fiber’s top surface and presses the fibers into the adhesive-filled V-grooves. The buffer prevents the adhesive, which is desired to flow and fill the region between the fibers, from contaminating the pick-tip. A fraction of the applied load, determined by the sliding plane angle, will be trigonometrically transferred to allow the chip to move towards the fiber tip (figure 2(e)). As standard fiber
components employ mechanical cleaving of fibers, there are small differences in fiber length from fiber to fiber that do not have a notable effect on the optical performance. The chip forward motion will stop when the longest fiber of the fiber stub array butts against its waveguide coupler. This contact will trigger the vertical force sensor on the pick and place tool based on a preset value. UV illumination is applied through the pick-tip and buffer for adhesive curing or tacking while the final assembly pressure is maintained. Finally the vacuum is released from both ports to allow the pick-tip to release the assembled part. The buffer layer secured by the cured adhesive remains on the assembled part, adding to the mechanical stability of the part and to the protection to the bare fibers.

III. ADDRESSING INCOMING FIBER PITCH VARIABILITY

Our original concept assumed that a coarse pre-alignment of fibers with an affixed lid was required to ensure the fibers were within the re-alignment range of integrated V-grooves on chip. We show in this section that the fiber positioning is notably more accurate than it would be expected from manufacturer’s specifications and as a consequence this pre-alignment may not be required.

A schematic cross-sectional view of the lateral re-alignment range is presented in figure 3. In our process, the friction is reduced due to the use of a low viscosity UV-curable optical adhesive pre-dispensed before assembly. Even without fiber rotation, the fiber will enter the V-groove if the static friction coefficient between the fiber and the oxide defining the V-groove opening is lower than the sine of the contact angle. The static friction coefficient of lubricated surfaces is generally lower than 0.5, including glass-glass interfaces in most situations [3]. Hence, it is reasonable to set this minimum contact angle to 30°, which then corresponds to a re-alignment capability of ±41μm. The residual misalignment in the final fiber position will depend on the fabrication tolerances of the V-groove and the fiber.

Considering that the placement accuracy on a standard high-throughput assembly tool is in the range of about ±10μm, each fiber of the incoming fiber array must then lie within ±31μm of an ideal position established by the pitch of the integrated V-groove array on chip for successful realignment.

The positional variability of bare fibers was characterized on procured fiber stubs. These include a short MT ferrule and a 12 fiber ribbon stripped and cleaved to a
5mm bare fiber length. Standard single-mode fibers with ~9 µm mode field diameter are used [4]. Thirty-six stubs were randomly selected from three different incoming lots. Each fiber stub lot was prepared with a different fiber ribbon spool. This precaution was deemed necessary to sample a representative distribution of incoming parts. The fiber positions were measured using an automated high-accuracy optical metrology system (OGP Smartscope Quest).

The measurement strategy is schematically represented in Figure 4. The automated tool program brings each individual fiber to focus and calculates its central position as the middle point between the two recognized edges. The reference axis Y is set by calculating the middle point of fiber 6 and the center of fiber 7, near the fiber tip, and then at 2mm away from this first measurement. The position of the fibers along the X-axis are then measured orthogonally from this Y-axis reference. For a 250 µm pitch target, the position of fibers 6 and 7 should be approximately 125 µm on either side of the origin of the X-axis while this distance should be of approximately 375 µm for fibers 5 and 8, 625 µm for fibers 4 and 9, etc.

The measurement results are presented in figure 5. The fiber pitch target is set by our current nanophotonic chips as 250 µm, the pitch of the V-groove array. This pitch could be adjusted lithographically to any value, however. The deviation from the target position of the fibers is presented for all fibers, by fiber number, in figure 5(a). Positive values on this graph indicate a larger distance from the middle of the fiber array than desired while a negative value indicates a smaller distance to the middle of the fiber array than desired. The data shows that the deviation increases gradually and positively as we move away from the central fibers (positions 6 and 7). This is in line with a fiber ribbon population having an actual pitch slightly higher than our 250 µm V-groove pitch. In fact, for color-coded single-mode fiber ribbons, the pitch is expected by major manufacturers to be slightly above 250 µm. Two outlier fiber stubs are highlighted in green and red in figure 5(a) showing notable stochastic variation in position from fiber to fiber.

The position of all the 432 fibers measured (12 fibers per stub and 36 stubs measured) falls within the assumed ±31 µm tolerance for the incoming fiber position discussed above. The statistical distribution, per fiber, was studied. A bimodal distribution was found for fibers 6 and 7, while a normal distribution was found for other fibers suggesting that additional statistical analysis could be beneficial. The boxplot presented in figure 5(b) shows the average value (center line), the 1st and 3rd quartile results (boxes) and the ±3-sigma extension (whiskers) for each fiber number. From this data, it is to be expected that a small number of incoming components could show peripheral fibers outside the assumed ±31 µm process limits.

As the proportion of potentially problematic fiber stubs is small, a larger statistical sample would be required to better assess the true amplitude of this concern and the corresponding yield management strategy to adopt in high-volume manufacturing. Performing a pre-screening of the incoming fiber stubs or rejecting defective assemblies could be considered from a logistic standpoint. In addition, a few technical improvements can be considered. First, the V-groove pitch on the chip could be adapted to better fit the fiber stub incoming distribution if this distribution remains stable between batches and through time. The effect of increasing the V-groove pitch by 1.2 µm is illustrated in figure 5(c). The effect of the 1.2 µm correction adds up as we move away from the central fibers with the result of flattening the solid curve representing the mean data (as shown by the solid blue and green lines in figures 5(b) and 5(c)). This simple example illustrates the V-groove position customization imparting a constant pitch adjustment. More data could reveal a more precise trend in the fiber position distribution leading to a more sophisticated customization of the fiber pitch. In addition, fine-tuning of the pick and place equipment and of the vision algorithms can provide a slightly better high-throughput vision positioning accuracy, to about ±7 µm. This would extend the assumed re-alignment range to ±34 µm and further reduce the probability of failure as illustrated in figure 5(c).

If the above solutions are found insufficient to achieve the yield target at high volume, it is also possible to use a pre-alignment comb to straighten the fibers before they are mounted on the chip. In a first implementation, the pre-alignment could be realized while the fiber stub is being picked by installing the comb on the placement tool head. Alternatively, the pre-alignment could be performed during the stub placement by adding the comb on the angled sliding plane just in front of the photonics chip. Such combs could provide a much larger re-alignment range than just a V-groove array on the chip and would be designed to provide coarse alignment only not to compete with the re-alignment...
by the integrated V-groove array, which is best positioned for fine alignment to the waveguide coupler.

IV. EXPERIMENTAL RESULTS

The novel assembly process with off-the-shelf fiber stubs was implemented with a dual vacuum pick-tip on a development assembly tool. The picking of the buffer and the fiber stub was automated with vision. The tool was chosen for its flexibility and convenience and the alignment routine did not employ the high accuracy placement capabilities of the tool. Hence, the results presented here are representative of assembly with high-throughput production tools.

The buffer pieces were prepared by dicing a UV-transparent polymer sheet and were then pre-loaded in a waffle pack for ease of use. The 12-fiber stubs with 5-mm-long bare fibers characterized in the previous section were assembled here to silicon photonics chips with 1 to 1.8 mm long built in V-grooves terminated with a metamaterial waveguide coupler embedded in a suspended oxide membrane [5-6].

Cross-sections of the assembled fiber stubs to a photonic chips were performed across the fiber plane at both the chip edge and near the suspended membrane area to confirm the proper seating of the fibers along the full length of the V-grooves. An example of a cross-section is presented in Figure 6. All fibers are well seated and make contact with the V-groove sidewalls warranting lateral and vertical alignment to fiber couplers on the chip. Additionally, the uniformity of the contact between the fibers and the buffer confirms adequate assembly parallelism between the pick-tip and the chip plane. The structural strength of the assembly is maximized by a uniform distribution of UV adhesive under the fiber and in the interstitial region between the buffer layer and the photonic chip.

X-ray tomography was also found very useful for assessing proper fiber placement and confirming the absence
of voids in the adhesive under the suspended membrane. It has the advantage of being a non-destructive method but its spatial resolution is lower than that of an optical micrograph. A virtual X-section obtained from an X-ray computed tomography scan (CT-scan) is shown in figure 7(a). It was taken in the plane of the silicon chip surface at the level of the fiber core. Good imaging contrast between the relatively low density materials can be obtained using a low-energy beam. The CT-scan reveals correct butting of the fibers on the left-hand side and a gap of ~15 μm between the fiber tip.
and the coupler waveguide for the last fiber on the right. A non-uniform buttongap is expected as the fiber length uniformity across the fiber ribbon is limited by the straightness of the mechanical fiber ribbon cleave used in standard off-the-shelf components. The slow divergence of the large standard single-fiber mode in the optical adhesive renders such moderate gaps not significant to optical performance. The level of detail achieved by X-ray tomography is difficult to obtain from top-down optical inspection despite all the top materials being transparent as the complex topography results in numerous optical artifacts.

Additional virtual cross-sections can be obtained from the same CT-scan. In figure 7(b), a side-view virtual cross-section is shown. The cavity under the suspended structure is completely filled with adhesive, a result that can be reliably obtained with adequate choice of adhesive chemistry. The proper alignment of the fiber core relative to the suspended membrane and their proximity along the butt-coupling axis can also be confirm within the 3μm spatial resolution limit of our X-ray tomography tool [7].

For a higher resolution assessment of the physical alignment between the fiber core and the coupler waveguide, we have developed a new sample preparation and optical microscopy methodology. The sample is first molded in epoxy and then polished from both the chip side and the fiber stub side in order to create a thin sample (see the cut-line on figure 8(a)). The sample is then backside illuminated from the fiber side on the microscope to highlight the fiber core, which will guide the illuminating visible light through total internal reflection. The remaining thin section of silicon waveguide coupler will occult the transmission of the light in such a way that, through the microscope objective, the silicon metamaterial waveguide core position will appear as a black
point overlaying the fiber core. The waveguide coupler mode is centered slightly above this metamaterial waveguide. An example of adequate alignment of fiber core to coupler waveguide is shown in Figure 8(c).

As a final validation of our novel approach to fiber assembly with off-the-shelf components, we present optical coupling measurements in Figure 9. A standard MT fiber patch cable was connected to the fiber stub. The 12 fiber ports on the chip were arranged in six loopbacks. The transmission loss shown here includes the MT connection loss at the patch cable to fiber-stub interface, the coupling loss at the fiber to waveguide-coupler interface, and the mode conversion loss from a standard cleaved single-mode fiber to a regular silicon bus waveguide on chip. The loss also includes propagation through the fiber stub and through half of the loopback on chip but both of these are assumed small. A dense Fabry-Perot spectral ripple on the TE polarization is related to an imperfection in the metamaterial mode converter, as described in [5]. In Figure 9(a), the effect of this undesired on-chip Fabry-Perot cavity was filtered out for clarity and the resulting curve overlaid on raw data. The four channels of the coarse wavelength division multiplexing (CWDMA) grid are highlighted in grey. One of the loopbacks was used as a polarization reference so its response is not shown here. A performance spread of up to \(-1\) dB is seen across the other ports, most of which can be attributed to assembly imperfections. The small polarization dependence of the loss is mainly attributed to mode conversion on chip.

V. Conclusion

We have demonstrated a novel approach to high-throughput automated assembly of single-mode optical fibers to nanophotonic chips. This time, our approach relies only on off-the-shelf fiber components without the need for customization with a pre-affixed lid. This reduces the overall process cost, complexity, and a few sources of variability. With the new approach, butt-coupling is obtained more repeatedly and using much less force than with our original implementation. This is a result of a lower force being required for lateral fiber re-alignment as no lid-to-fiber adhesive hinders the fiber movement. A reduction in the vertically applied force lowers the stress imposed by the longest fibers to the suspended membrane and the risk of damaging the waveguide coupler. On the flipside, our statistical data indicates that a small proportion of fiber stubs could have peripheral fibers beyond the anticipated re-alignment range. Overall, we believe the benefits of having non-restricted, free-standing bare fibers which can almost freely re-position themselves during assembly, overcome the previously expected benefits of having the fibers coarsely pre-aligned using the pre-attached lid.

We believe this novel approach will further improve cost-efficiency and scalability of high-throughput parallelized fiber assembly to photonic chips, contributing to fulfill the potential of silicon photonics.

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