Mechanically Flexible Chip-to-Substrate Optical Interconnections Using Optical Pillars

Muhammad S. Bakir, Member, IEEE, Alexei L. Glebov, Senior Member, IEEE, Michael G. Lee, Paul A. Kohl, Member, IEEE, and James D. Meindl, Life Fellow, IEEE

Abstract—We experimentally characterize the benefits of using surface-normal mechanically flexible optical waveguides, or optical pillars, for chip-to-substrate optical interconnection. In order to benchmark the performance of the optical pillars, the optical coupling efficiency from a light source to an optical aperture with and without an optical pillar is measured. For a light source with 12° beam divergence, a 50 × 150 µm optical pillar improves the coupling efficiency by 2–4 dB compared to pillar-free (free-space) optical coupling. A 30 × 150 µm optical pillar improves the coupling efficiency by 3–4.5 dB. This demonstrates the importance of using optical pillars when small photodetectors (PDs) and dense optical input/output (I/Os) are needed. The optical excess losses of 50 × 150 µm optical pillars are measured to be less than 0.2 dB. Due to the high mechanical flexibility of the pillars, we also demonstrate that optical pillars enhance the optical coupling efficiency between the chip and substrate when they are misaligned in the lateral direction. This is especially important since the coefficient of thermal expansion of the chip and substrate are often mismatched, and preserving optical alignment and interconnection between them is critical during thermal excursions. The lateral mechanical compliance of the optical pillars is also measured and can be as great as 30µm/mN. The optical pillars are also shown to be compliant under a compressive force thus allowing the optical I/Os to be assembled on nonplanar surfaces such as low-cost organic substrates.

Index Terms—Assembly, compliant interconnects, flip-chip, input/output (I/O), integration, optical interconnects, packaging, polymers, waveguides.

I. INTRODUCTION

A key bottleneck to the realization of high-performance microelectronic systems is the lack of low-latency and high-bandwidth off-chip interconnects. Some of the challenges in achieving high-bandwidth chip-to-chip communication using electrical interconnects include the high losses in the substrate dielectric, reflections and impedance discontinuities, and susceptibility to cross-talk. As a result, the motivation for the use of microphotonics technology to overcome these challenges and leverage low-latency and high-bandwidth chip-to-chip communication has been presented [1]–[3]. Significant progress has been made in developing chip-to-chip optical interconnects. Fiber-to-the-chip schemes, where an optical signal is coupled to a silicon integrated circuit through nanoscale silicon-based waveguides have been reported [4]. However, such an approach limits the optical input/output (I/O) density (because of fiber size and handling), increases the complexity of packaging, and potentially increases the cost of assembly because fibers must be manually (serial process) connected to each chip. High-density free-space optical interconnects are also being pursued for chip-to-chip communication [5]–[7]. However, susceptibility to misalignment and complexity in packaging are formidable challenges that have yet to be fully addressed.

Guided-wave optical interconnects using polymer waveguides, which are batch fabricated on the substrate, are being pursued as an alternative to free-space optical I/O transmission ([8]–[19], and references therein). Polymer-based optical waveguides offer a number of advantages that include high density, optical confinement, and ease of fabrication. In addition, this optical interconnection approach is compatible with flip-chip technology because the physical structures are similar in size. The optical signal is routed through a waveguide to a point beneath the chip where chip-level optical sources and photodetectors (PD) are located. Fig. 1 illustrates three methods of achieving surface-normal optical interconnection between
the chip and the substrate-level optical waveguides. In all cases, mirror-terminated waveguides are positioned directly beneath the chip-level optical sources and PDs. In the first two cases [Fig. 1(a) and (b)], however, optical interconnection is achieved through free-space transmission. In the latter case, microlenses are used to focus the light from the mirror to the PD and from the vertical cavity surface emitting laser (VCSEL) to the mirror in order to control beam divergence. The free-space optical I/O transmission, shown in Fig. 1(a), places significant constraints on the 3-D spatial positioning of the optical elements relative to each other. The chip cannot be placed too far above the mirror because the reflected light will spread causing a decrease in the optical power received by the detector. The use of lenses [19] to focus the light, as shown in Fig. 1(b), adds fabrication complexity and requires relatively large lenses. In addition, the direct coupling scheme of Fig. 1(a) is highly susceptible to lateral alignment deviations caused either during assembly or thermal cycling. This is especially important in conventional chip-on-substrate schemes where there is a coefficient of thermal expansion (CTE) mismatch between the chip and substrate. Today, the CTE mismatch between the Si chips and the organic epoxy-based substrates that they are mounted on is approximately 14 ppm/°C. This translates into a thermomechanical induced misalignment of approximately 10 μm at the corner of a 1.5 × 1.5 cm² chip for a temperature excursion of 60 °C. Such misalignments can severely reduce the optical power delivered to the PD thereby increasing the bit error rate (BER) [20] and reducing bandwidth. Moreover, such free-space optical I/O schemes are not compatible with underfill processes. Depending on chip size, underfill may become essential to insure the reliability of the solder bumps during thermal cycling. A competing approach to address the CTE mismatch issue is the use of mechanically compliant leads such as high aspect ratio flexible metal pillars [21]–[23], metal coated polymer bumps [24]–[30], and 3-D flexible metal leads (31]–[33], and references therein). As a result, it is important to develop an optical I/O technology that is compatible with both compliant leads and solder bumps, which may require underfill (depending on chip size).

The use of flexible surface-normal optical waveguides, or optical pillars, was previously described as a means of addressing the shortcomings of free-space optical I/O interconnections [29], [30], [34]. Optical pillars resemble optical fibers with the main difference being that they are air clad, which increases the index of refraction difference between the core and cladding thereby creating tightly bounded modes. Fig. 1(c) illustrates how the optical pillars provide optical interconnection between the chip and the substrate. The height separation between the chip and the substrate has virtually no effect on the optical power received at the PD (except for excess losses) because the light is tightly confined within the cross-sectional area of the pillar. Although we consider using polymeric materials with relatively high optical absorption losses for the fabrication of the optical pillars, due to their very short length (height), the optical transmission losses through the pillars are small as will be shown in this study. Optical coupling between a planar polymer waveguide and an optical pillar has been recently demonstrated using a mirror [35]. The optical pillars are designed to be mechanically compliant (flexible). The low elastic modulus of the polymer and air cladding of the waveguide contribute to the flexible nature of the optical pillars. As a result, the lateral misalignment induced by chip-substrate CTE mismatch is compensated by the mechanical compliance of the optical pillars. Thus, optical interconnection and alignment are maintained at all times between the optical components on the chip and substrate due to the mechanical compliance of the optical pillars. As a result, the optical I/O technology under consideration is fully compatible with mechanically compliant electrical I/Os as well as solder bumps. When underfill is needed for the latter, the optical pillars provide a low-loss path through the underfill film and can be coated with a layer of silicon dioxide for the cladding.

In this paper, we experimentally benchmark the performance of the optical pillars with free-space optical I/O transmission as well as characterize the out-of-plane and in-plane mechanical compliance of the optical pillars thereby experimentally demonstrating the benefits of such interconnect structures. To this end, the paper is organized as follows. First, we begin by describing the key polymer properties needed for the optical pillars and their fabrication in Section II. Section III describes the optical loss measurements of the optical pillars. The optical coupling efficiency between a light source and two different sized apertures (30 μm and 50 μm diameter) with and without optical pillars is described in Section IV. The in-plane and out-of-plane mechanical compliance of the optical pillars and resulting improvements in the optical coupling efficiency due to lateral displacement compensation of the pillars are presented in Section V. Finally, Section VI is the conclusion.

II. MATERIAL PROPERTIES AND FABRICATION

The material property requirements for the optical pillar waveguides differ from those required for polymer chip-to-chip optical interconnects. The reason is because the typical distances that each traverses are dramatically different. While chip-to-chip and backplane optical interconnects can be greater than 20 cm and 60 cm, respectively, in length, the distance between the chip and the package substrate is less than 300 μm in most applications. In fact, the gap between a microprocessor chip (die) and the package substrate today is less than 100 μm, and it is expected to decrease in the future due to the ever shrinking size of solder bumps. As a result, the optical absorption losses of the polymer used for the fabrication of the optical pillars can be higher than those typically used for chip-to-chip. The optical power loss (P_{loss}) as a function of distance (L) can be described as [36]

\[ P_{loss} = P_{in} e^{-\alpha_{wg} L} \]  

where \( P_{in} \) is the input power and \( \alpha_{wg} \) represents the total losses (radiation, scattering, and absorption) of the waveguide. Ignoring radiation and scattering losses, Fig. 2 illustrates the calculated optical transmission of an optical pillar as a function of length (height) and absorption losses using this simple approximation. The figure illustrates that due to the short length of the pillars, a 100-μm-tall optical pillar will cause a 2% loss of optical power assuming a polymeric material with a 10 dB/cm absorption loss (which would be impossible to use
Fig. 2. Calculated optical transmission of a waveguide as a function of length (height of pillar) and polymer absorption loss.

Table 1

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Processing Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_s$</td>
<td>250 °C</td>
</tr>
<tr>
<td>Modulus</td>
<td>0.5 GPa</td>
</tr>
<tr>
<td>CTE</td>
<td>&gt;55 ppm</td>
</tr>
<tr>
<td>Moisture absorption</td>
<td>0.13%</td>
</tr>
<tr>
<td>Index of refraction (@ 632 nm)</td>
<td>1.52</td>
</tr>
</tbody>
</table>

Fig. 3. Schematic illustration of the fabrication process used in this work to fabricate the optical pillars.

Since the goal of this work is to optically and mechanically characterize the optical pillars, it is important to fabricate the optical pillars in a way as to permit optical access to both ends. To this end, the optical pillars are fabricated above metal apertures on a transparent glass substrate. The fabrication process that was used is shown in Fig. 3. A metal film is first deposited and patterned on a glass substrate [Fig. 3(b)]. In this case, a 600-nm-thick layer of Al was used. Next, silicon dioxide is deposited above the patterned metal film to enhance the adhesion of the optical pillars to the substrate. The polymer is next spin coated above the silicon-dioxide layer followed by a soft bake on a hotplate set to 100 °C [Fig. 3(c)]. The polymer film is next ultraviolet (UV) irradiated (365 nm) in either of two ways. If the diameter of the optical apertures is equal to the diameter of the desired pillars, back-side exposure can be used, as shown in Fig. 3(d). Here, by mounting the substrate upside down in a mask aligner, the same optical apertures that would be used for optical testing are used as a mask to photopattern the polymer with the cross-sectional geometry of the pillars. Otherwise, a second mask is used to fabricate the desired shape and diameter pillars on the optical apertures, as illustrated in Fig. 3(e). Following UV irradiation of the polymer film, the glass wafer is placed in a nitrogen purged oven (100 °C) for a hard bake. Next, the polymer film is spray developed using Avatrel Developer to yield the optical pillars [Fig. 3(f)]. Finally, the wafer is placed in a nitrogen-purged oven where the polymer is cured at a temperature of 160 °C. Fig. 4 illustrates scanning electron microscope (SEM) images of 30-μm-diameter and 150-μm-tall optical pillars fabricated above optical apertures. In addition, 50-μm-diameter and 150-μm-tall optical pillars were fabricated. All optical pillars used in this work were fabricated using the back-side exposure method.

III. MEASURED OPTICAL PILLAR LOSSES

All optical measurements reported in this paper were carried out using a VCSEL-based 850-nm optical source. The light is coupled to the test pillar sample either through a standard multimode optical fiber with a 50-μm core diameter or with a lens terminated fiber. Fig. 5 illustrates the light beam divergence measurements of the two light sources used in this paper to char-
characterize the optical pillars. The measurements were performed with a slit-based beam profiler. The beam width is measured at different distances from the source and the linear fit provides the exact value of the light beam divergence angle. The figure shows that the multimode fiber exhibits a 7° beam divergence. The lensed source has a divergence angle of 12°, which is similar to divergence of a typical multimode VCSEL.

The experimental setup used to measure the excess loss of the optical pillars is shown in Fig. 6. A multimode glass fiber with a core diameter of 50 μm is laterally scanned across the endface of the optical pillar and across the surface of the metal aperture. In this measurement, the light source with the 7° divergence angle was used. A mode scrambler in the path of the light ensures uniform light mode distribution at the pillar input. Using this experimental setup, the excess loss of the 50-μm-diameter pillars was measured. The relative transmitted intensity of the optical pillar (plus glass substrate) is plotted in Fig. 7(a) as a function of fiber position (light source) along the X- and Y-axis. The transmitted intensities are normalized to the maximum transmission at the center of the aperture without a pillar. Due to radial symmetry of the light source and the pillars, the scans in the X-axis and in the Y-axis are practically identical. The difference between the measured transmitted intensities (using data from the X-axis scan) for the two cases (pillar versus no pillar) is plotted in Fig. 7(b). The excess loss of the pillar at the center ($X = 0 \text{ μm}$) is well below the 0.1 dB resolution limit of the test equipment. Thus, for the 50 × 150 μm pillars, the excess loss is essentially negligible at the center of the pillar. The excess loss away from the center does not exhibit radial symmetry. This is possibly due to the cleanliness of the glass-surface at the pillar interface versus the pillar-free sites (i.e., more particles adhered to one site than the other). This may also be due to particles or other contaminants in the polymer film, thus necessitating additional filtering before spinning the polymer onto the substrate. The highest recorded excess loss is 0.23 dB at $X = -10 \text{ μm}$. At positions offset from the center of the pillar, the light intensity decreases by less than 5% at ±10 μm lateral displacement. This value is in agreement with the calculated percentage transmission loss shown in Fig. 2 for a 150-μm
tall optical pillar (using interpolation between the "100-μm-tall pillar" and "300-μm-tall pillar" lines) at 10 dB/cm optical absorption, which was previously measured for this polymer [21]. Shorter optical pillars are expected to demonstrate smaller excess loss.

IV. OPTICAL PILLAR ATTRADED COUPPING EFFICIENCY IMPROVEMENTS

Fig. 8 illustrates the experimental setup used to characterize the surface-normal optical coupling efficiency of the pillars. In this measurement, the light source with the 12° divergence angle (Fig. 5) was used. The fiber was scanned in the X-axis and in the Y-axis across the endface of the pillar and across the surface of the aperture (at a Z-axis distance equal to the pillar’s height). The transmitted optical power was measured with a Si detector as a function of the fiber (light source) position in the lateral direction. This measurement setup represents a benchmark of the optical I/O schemes illustrated in Fig. 1(a) and (c).

The relative transmitted optical intensity measurements of the 50 × 150 μm optical pillars and 50-μm optical apertures are plotted in Fig. 9(a). The transmitted intensities are normalized to the maximum transmission at the center of the aperture without a pillar. Again, the X- and Y-axis scans are essentially equal due to the radial symmetry of the light source and the pillars. The difference between the coupling efficiency of the two measurements (using data from the X-axis scan) is plotted in Fig. 9(b). The data clearly demonstrate that at the 0-μm displacement position, the optical pillars enhance the coupling efficiency by approximately 2 dB when compared to direct coupling into the aperture. At distances of ±25 μm away from the center, the optical coupling improvement due to the pillar exceeds 4 dB. The 4 dB coupling improvement is significantly larger than the 0.23 dB excess loss of the pillars, which clearly demonstrates the benefits of the pillars. Note that the profile of the relative intensity curve of the optical pillar is almost flat across the entire endface of the pillar and abruptly drops beyond the edges of the pillar (X = ±25 μm). On the other hand, the intensity curve of the aperture resembles an inverse parabola. This is important because it signifies the importance of having perfect alignment for the direct coupling case shown in Fig. 1(a). Any misalignment in the lateral direction would cause a fast roll-off in the intensity. Even with perfect alignment during assembly, any lateral misalignment between the mirror and the detector due to either CTE mismatch or other factors may reduce the coupling.
efficiency and limit the achievable bandwidth. Moreover, this demonstrates that the optical crosstalk between adjacent I/Os is eliminated through the use of the optical pillars.

In order to confirm the coupling efficiency measurement over the 50-μm aperture, the fiber was aligned to the center of the aperture and moved vertically away from the surface of the aperture. The coupling loss as a function of Z-axis separation is plotted in Fig. 10. At Z = 150 μm, the coupling loss is approximately 2.2 dB, which confirms the data shown in Fig. 9. Increasing the separation further to 300 μm causes the coupling loss to approach 6 dB. This clearly demonstrates that the coupling efficiency in free-space optical I/O transmission is susceptible to Z-axis separation. The data suggest that at separations of less than 50 μm, the optical pillars may not provide significant improvement in the coupling efficiency (in the case of 50-μm aperture) as the coupling loss is less than 0.5 dB. However, using an optical pillar at such a small separation will not degrade the coupling efficiency either as the excess losses of the pillar will be practically negligible. As we will show in Section IV, the mechanical compliance of the optical pillars improves the coupling efficiency during lateral offsets. For chip-to-substrate separations greater than 60 μm, the 50-μm-diameter optical pillars provide appreciable improvement in the optical coupling efficiency.

Similar measurements were made for the 30 × 150 μm pillars (optical aperture 30 μm in diameter). Using the experimental setup shown in Fig. 8, the transmitted optical intensities for both cases are plotted in Fig. 11(a). The difference between the transmitted intensities using the data from the X-axis scan is plotted in Fig. 11(b). The optical pillar improves the coupling efficiency by 3–4.5 dB. This improvement in the optical coupling efficiency is larger than the measured improvement from the 50 × 150 μm pillar. This is significant as it clearly demonstrates that as the optical I/O density increases and smaller PDs are used to attain higher bandwidth, optical pillars become even more critical to the overall performance of the system.

The coupling loss as a function of Z-axis separation over the 30-μm-diameter aperture is plotted in Fig. 12. At Z = 150 μm, the coupling loss is approximately 4.2 dB and confirming data shown in Fig. 11. Increasing the separation further to 300 μm causes the coupling loss to approach 10 dB, which is larger than the 6 dB loss for the 50-μm aperture. This again demonstrates that with the use of smaller PDs for higher bandwidth and higher I/O density, the importance of 3-D spatial positioning of the optical components is increased, which makes direct coupling into a PD without a pillar difficult to implement. For example, the coupling loss of the 30-μm-diameter aperture at Z = 100 μm is 2 dB compared to 1 dB for the 50-μm-diameter aperture. At Z = 200 μm, the coupling loss is 6 dB for the 30 μm diameter aperture and less than 4 dB for the 50-μm-diameter aperture. Thus, the coupling loss for the 30-μm-diameter aperture exhibits greater dependence on Z-axis separation (the slope of
the intensity curve is greater). The optical pillars essentially eliminate the dependence of the coupling efficiency on Z-axis separation.

V. LATERAL DISPLACEMENT COMPENSATION USING OPTICAL PILLARS

We have previously described the improvement in optical coupling efficiency as a result of the lateral displacement compensation of the compliant optical pillars [36]. In this section, we expand this analysis. In order to understand the flexible nature of the optical pillars, the lateral and vertical mechanical compliance of the optical pillars were measured at room temperature using a Hysitron TribolIndenter. The experimental setup for the lateral compliance measurements is shown in Fig. 13. In order to measure the force-displacement characteristic curve of the optical pillar in the lateral direction, a silicon die containing the optical pillars was mounted sideways in the Hysitron TribolIndenter, as shown in Fig. 13. The measured force-displacement characteristic curve of an optical pillar that is approximately $57 \times 170 \mu m$ is shown in Fig. 14. The peak displacement of the optical pillar was limited by the test equipment and is equal to 5 $\mu m$. The measured data indicate that the optical pillar undergoes elastic deformation up to the 5 $\mu m$ peak displacement possible by the test equipment. As indicated by the unload curve, the optical pillar returns to its original position following the removal of the load. The compliance of the pillar can be calculated by dividing the peak elastic displacement by the applied force and is equal to 5.5 $\mu m/mN$ in this case. The compliance of the pillars significantly increases as their length (height) increases or as their diameter decreases. For example, the compliance of an optical pillar that is approximately $57 \times 300 \mu m$ was measured to be greater than 30 $\mu m/mN$. Assuming beam-like properties (high aspect ratio values approaching 10:1), the mechanical compliance of a pillar is inversely proportional to the elastic modulus ($E$) of the material from which it is fabricated from [39]. The compliance ($C$) of a beam of length $L$ can be expressed as [39]

$$C = \frac{x}{F} = \frac{L^3}{3EI}$$

where $x$ and $F$ are the lateral deflection and applied force (at beam’s tip), respectively, $I$ is the second area moment of inertia of the beam. For the geometry under consideration, in which the pillar resembles a cylinder, $I$ can be expressed as [27]

$$I_{cylinder} = \frac{\pi}{4} r^4$$

where $r$ is the radius of the cross-section. It is clear that as the radius increases, the compliance decreases rapidly. From (2), it is also clear that the use of a low modulus polymer increases the mechanical compliance of the pillars. If the pillars were fabricated using SU-8, which exhibits an elastic modulus of approximately 4 GPa, and assuming beam-like properties (high-aspect ratio pillars), it is expected that the mechanical compliance will decrease by a factor of 8.

The experimental setup for vertical compliance measurements is shown in Fig. 15. A 200-$\mu m$-radius tip was used to indent the optical pillars. Table II illustrates the set of data for optical pillars that are 110 $\mu m \times 55 \mu m$ after being cured at 200 °C. The maximum force (mN) and the loading rate ($\mu N/s$) were programmed into the software controlling the indentor and are shown in the table. The exact (measured) applied force and the resulting displacement of each tested pillar are also reported in the table. While the radius of the indentor tip was $\sim 200 \mu m$, the radius of the tested optical pillars was $\sim 27.5 \mu m$. Thus, the indentor tip is almost an order of magnitude larger is diameter than the tested optical pillars. As a result, it can be assumed that the total measured force is applied over an area equal to the area of the endface of the pillar. For every 1 mN of force, the net applied stress is 421.1 mN/mm². Considering the measurement of structure A2 in Table II, the optical pillar was compressed by approximately 3.5 $\mu m$ at 25.3 mN (10.65 N/mm²). The cured optical pillars
Summary of the Data Obtained Using the Experimental Setup Shown in Fig. 15

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Structure description</th>
<th>Max force (mN)</th>
<th>Loading rate (mN/s)</th>
<th>Indent duration (s)</th>
<th>Measured force (mN)</th>
<th>Measured displacement (μm)</th>
<th>Disp. - Force ratio (μm/mN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td></td>
<td>25</td>
<td>100</td>
<td>505</td>
<td>25.05</td>
<td>3.8</td>
<td>0.15</td>
</tr>
<tr>
<td>A2</td>
<td></td>
<td>25</td>
<td>1000</td>
<td>55</td>
<td>25.30</td>
<td>3.5</td>
<td>0.14</td>
</tr>
<tr>
<td>A3</td>
<td></td>
<td>5</td>
<td>100</td>
<td>105</td>
<td>5.18</td>
<td>0.79</td>
<td>0.15</td>
</tr>
<tr>
<td>A4</td>
<td></td>
<td>5</td>
<td>1000</td>
<td>15</td>
<td>5.24</td>
<td>0.73</td>
<td>0.14</td>
</tr>
<tr>
<td>A5</td>
<td>110 μm x 55 μm, 4 hr cure at 200°C</td>
<td>600</td>
<td>40,000</td>
<td>35</td>
<td>600.7</td>
<td>61.3</td>
<td>0.102</td>
</tr>
</tbody>
</table>

Fig. 16. Schematics of the experimental setups used to evaluate the optical displacement compensation of the pillars.

Deform elastically at relatively small deformations. This can be verified from the data shown in Table II. When the applied force was decreased by a factor of 5, the pillar's compression also decreased by a factor of approximately 5, or 0.73 μm (A4 in Table II). It was also found that the loading rate does not significantly affect the data indicating that the cured pillars do not undergo significant creep. This was in contrast with data from the pillars before cure, in which creep significantly altered the displacement results.

The experimental setup used to characterize the optical displacement compensation of the optical pillars is shown in Fig. 16. To quantify the effects of pillar bending on optical signal transmission, two experimental configurations, shown in Fig. 16, were developed. In the first configuration, which is labeled “scanning” in the figure, the light source (fiber) is scanned laterally across the endface of the pillar (similar to earlier measurement). In the second configuration, which is labeled “pillar bending” in the figure, the fiber is attached to the endface of the pillar using epoxy to form an air-free light path between the source and the substrate. This configuration is equivalent to the optical I/O interconnection method shown in Fig. 1(c), in which the pillars optically bridge the chip-substrate gap. In the “pillar bending” case, the controlled lateral displacement of the light source causes the optical pillar to bend sideways helping to keep the lightmode confined in the pillar and thus, to deliver the optical signal to the detector with lower coupling losses.

The relative transmitted intensities as a function of lateral displacement of the light source for the two experimental configurations illustrated in Fig. 16 are shown in Fig. 17(a). Due to radial symmetry of the light source and optical pillar, the measured intensity in the X-axis and Z-axis are practically identical. The bending range of the pillar is limited by the elasticity of the pillar and its adhesion at the top and bottom interfaces. As can be seen in Fig. 17(a), the 50 x 150 μm pillar can bend sideways by 50 μm. This demonstrates that the optical pillars can bend significantly more than the 5-μm peak displacement limitation of the mechanical test equipment described above. The optical transmission is measured during the forward bending of the pillar and as it returns to its original position. The data shows no significant hysteresis.
As can be seen from Fig. 17, the use of the refractive index matching epoxy to glue the fiber to the endface of the pillar decreased the optical losses at zero displacement by 0.2–0.3 dB. Thus, by simply eliminating the air-gap between the pillar and the optical source, one automatically gains a reduction in the coupling loss because the air-free pass minimizes the Fresnel back-reflections. Fig. 17(b) shows the loss reduction due to the use of pillar bending at different light source displacements. The loss reduction is less than 1 dB up to ~15 µm displacement, while it increases up to 4 dB at 30 µm. This is significant since a limited loss budget is available in typical systems for misalignments/assembly to maintain error-free operation. Fig. 17(a) demonstrates that for a given loss budget of, e.g., 1 dB, the 50 × 150 µm flexible pillars double the displacement tolerance from less than 15 µm to approximately 30 µm. The 4 dB pillar-assisted loss reduction at the 30 µm displacement can easily decrease the BER by 10^4 or more. Thus, the optical pillars provide a method of reducing optical coupling losses caused by thermomechanically induced misalignment between the CTE mismatched chip and substrate. Based on the above, it is clear that chip assembly and displacement tolerances are among the critical issues as they make a strong impact on the cost of the optical interconnect modules and thus, contribute directly to the competitiveness of the optical interconnect approach. The BER of a computing digital system is typically expected to be lower than 10^-12 and, sometimes, even lower than 10^-15. Since the BER depends strongly on the detector sensitivity and the strength of the output optical signal, minimization of the total optical power loss of the optical interconnect module is of key importance for keeping the BER low.

VI. CONCLUSION

The use of optical pillars to enhance surface-normal optical coupling efficiency between chip-level optical devices and substrate-level waveguides is experimentally demonstrated. The improvements in the optical coupling efficiency when optical pillars are used to interconnect a light source and an optical aperture are reported. When 50-µm-diameter apertures and 50 × 150 µm pillars are used, the improvement in the coupling efficiency due to the optical pillars is 2–4 dB. When 30-µm-diameter apertures and 30 × 150 µm pillars are used, the improvement in the coupling efficiency due to the optical pillars is 3–4.5 dB. These improvements could improve the BER of a digital system by orders of magnitude. This is also significant as it clearly demonstrates that as the optical I/O density increases and smaller photodetectors are used to attain higher bandwidth, the use of optical pillar waveguides becomes critical to the overall performance of the system. The coupling improvements are much higher than the excess losses of the pillars, which do not exceed 0.23 dB. Moreover, the mechanical compliance of the optical pillars significantly improves the displacement tolerance of the assembled parts, which is especially important due to the CTE mismatch between the chip and substrate. The displacement tolerance is doubled from 15 to 30 µm in the case of the 50 × 150 µm pillars for a 1 dB power loss budget. It is expected that the optical pillars with larger aspect ratios and smaller diameters can provide even higher displacement compensation in dense chip-to-chip optical interconnect modules. The out-of-plane compliance of a 55 × 110 µm optical pillar is measured to be 0.14 µm/mN, while the lateral compliance of a 57 × 170 µm optical pillar is measured to be 5.5 µm/mN.

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REFERENCES


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