Flexible Pillars for Displacement Compensation in Optical Chip Assembly

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***Abstract*—In chip-to-chip optical interconnect systems with surface mounted light-sources and detectors, thermal and mechanical effects can cause lateral displacements of the assembled devices. These displacements can result in optical signal losses that can critically deteriorate the bit-error-rate of the digital system. We demonstrate that, for a given loss budget of 1 dB, the use of flexible optical pillars with 150-μm height and 50-μm diameter can double the lateral displacement tolerance from about 15 to 30 μm. The pillars fabricated from Avatrel polymer form an air-free path between the light source and the substrate and cause maximum optical power losses less than 0.2 dB.**

***Index Terms*—Optical assembly and packaging, optical interconnects (OIs), polymers, waveguides.**

I. Introduction

PHOTONIC technologies become of growing interest for short-reach communication applications, such as board-to-board and chip-to-chip optical interconnects (OIs). A number of laboratory solutions have been proposed for high-speed chip-to-chip OI [1] and the technologies are maturing rapidly toward commercialization. The use of surface mount technology (SMT) can provide a robust and cost-effective assembly for vertical-cavity surface-emitting lasers (VCSELs) and photodiodes (PDs) on OI substrates [2], [3]. Chip assembly and displacement tolerances are among the critical issues as they make a strong impact on the cost of the OI modules and, thus, contribute directly to the competitiveness of the optical approach.

The bit-error-rate (BER) of a computing 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 OI module is of key importance for keeping the BER low. For example, additional power losses of 1 dB can setoff the BER increase by several orders of magnitude (e.g., [4]). Thus, it is critical to have sufficient optical power at the detector, and to maintain the optical signal stability during the system operation.

In this work, test chips with flexible optical pillars are fabricated and the optical characteristics are measured. The results clearly demonstrate that the pillars strongly increase the displacement tolerances of the assembled chips with virtually no accumulated excess losses and, therefore, can significantly improve the stability of an OI system operation.

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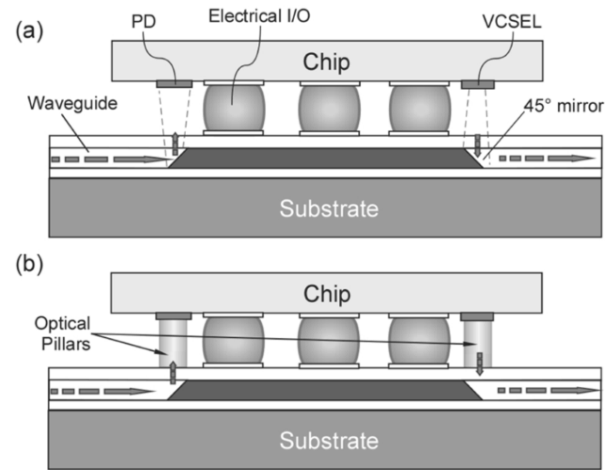

Fig. 1. Schematics of optical chip assembly with the (a) direct and (b) pillar-assisted light coupling between the VCSEL/PD and substrate waveguides.

II. Results

The SMT chip assembly is schematically depicted in Fig. 1(a). The light couples directly through the air between the 45° reflector mirrors [5] of the substrate waveguides and the VCSEL/PD on the chip. Various thermal and mechanical effects such as CTE mismatch, substrate bow, and chip bow can cause lateral displacements of the chip relative to the substrate resulting in the optical power loss in the system and consequential deterioration of the BER. One way to improve the displacement tolerance is to mount microlenses or microlens arrays between the light sources and the substrate [2], [5]. However, microlens fabrication, assembly, and alignment can add considerable cost to the OI module and also pose some system design constrains such as the channel density, distances from the source to the waveguide mirrors, and underfill use.

Flexible high-aspect ratio polymer pillars were recently introduced for the input–output (I/O) interconnections in gigascale integration [6]. The pillar-assisted assembly of a chip is visualized in Fig. 1(b). Although solid pillars have no advantages in terms of displacement compensation, flexible pillars can be used to accommodate the lateral shifts.

In this work, flexible optical pillars are fabricated from polynorbornene-based dielectric polymer Avatrel 2000P[1] [7]. Avatrel has many attractive properties for dense photonic integra-

[1]Optical and thermomechanical properties of Avatrel 2000 can be found at http://www.promerus.com

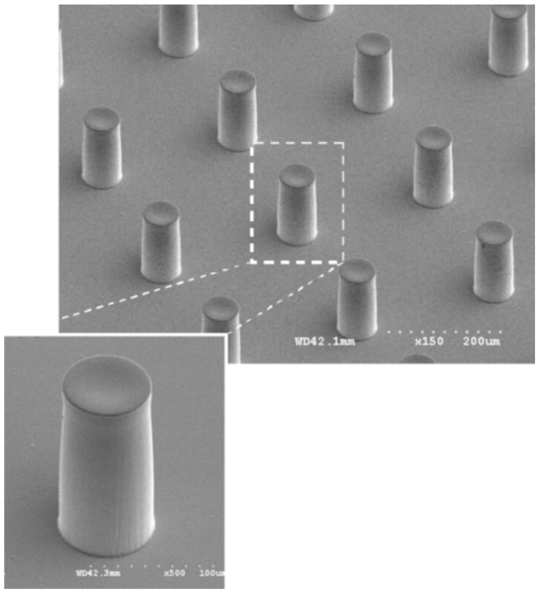

Fig. 2. SEM images of Avatrel pillars with 150-μm heights and 50-μm diameters. The pitch is 250 μm.

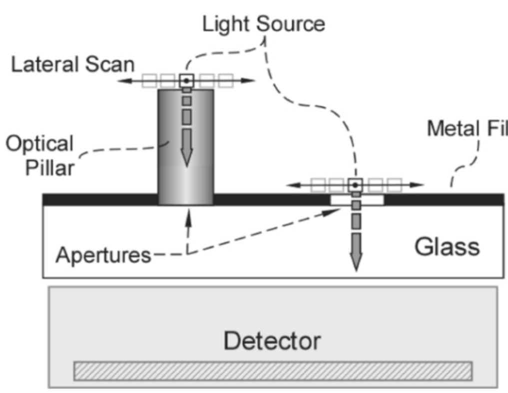

Fig. 3. Testing structure for the pillar optical excess loss measurements.

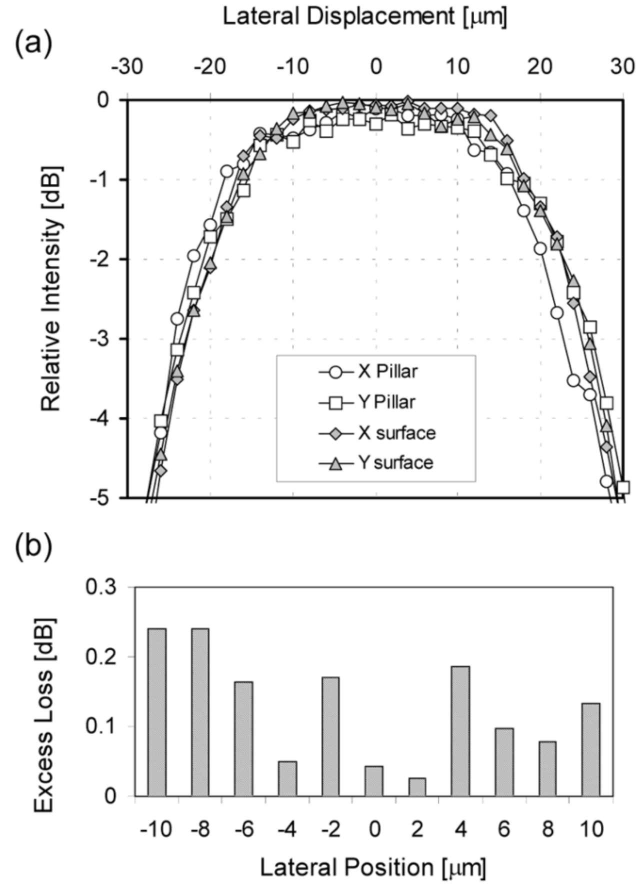

Fig. 4. (a) Relative transmitted intensities as a function of the light source lateral displacement measured at the pillar top and directly at the substrate surface. (b) Pillar excess losses at different positions of the input light source.

tion, such as photosensitivity, high Tg $> 280\ ^\circ$C, high transparency, refractive index range 1.5–1.55, good adhesion to a variety of materials, and low stress. Moreover, the low modulus (0.5 GPa) and high elastic flexibility make Avatrel a good candidate for highly flexible pillars. Pillars with different aspect ratios up to $1:8$ (height-to-diameter) can be formed lithographically from Avatrel. The pillars with a diameter of 50 μm and height of 150 μm are used for the optical experiments reported below. The scanning electron microscope (SEM) images of some exemplary 50×150 μm Avatrel pillars are shown in Fig. 2.

The test chips are fabricated in the following process. The 400-nm-thick Al is sputtered on a 500-μm-thick glass substrate. An array of round apertures with a pitch of 250 μm are lithographically opened in the metal film and a 1-μm-thick silicon nitride layer is deposited on top of the sample to improve adhesion to Avatrel. The Avatrel layer is spin-coated on top of the nitride film and the pillars are photopatterned with the second mask matching the positions of the round openings in the metal layer. In this configuration, shown in Fig. 3, the light is launched into the pillar top perpendicular to the substrate.

The light propagates through the pillar and the glass substrate and is captured by the PD mounted behind the test sample. Some of the metal apertures are left free of pillars so that the light transmission could be measured directly at the substrate surface, as illustrated at the right-hand side of Fig. 3. The light transmission through the pillar and substrate is compared through the substrate only, to provide a measure of the pillar excess loss.

A multimode 850-nm VCSEL is used as a light source and the light from the VCSEL propagates to the pillars through a glass fiber with a 50-μm diameter core. A mode scrambler in the light pass ensures the uniform light mode distribution at the pillar input. The position of the light source fiber output is scanned in lateral directions, X and Y, along the top surface of the pillar while the detector records the transmitted light intensity as a function of the lateral position of the source. The intensity as a function of lateral position along the top of the pillar and along the top of the aperture at the glass substrate surface is shown in Fig. 4(a). The transmitted intensities are normalized to the maximum transmission at the center of the open aperture without a pillar. All loss measurements are performed with continuous light. Since the pillar optical pass is only 0.1–0.2 mm, it should not show different loss dependence for high-speed modulated light and have any significant effect on the modal dispersion, which may lead to the BER increase.

The pillar excess losses, shown in Fig. 4(b), are obtained by subtracting the relative intensities at different lateral positions in the X-direction for the pillar and no pillar cases from Fig. 4(a). The data presented in Fig. 4(b) reveal that the pillar excess losses in the ± 10-μm displacement range from the pillar center do not

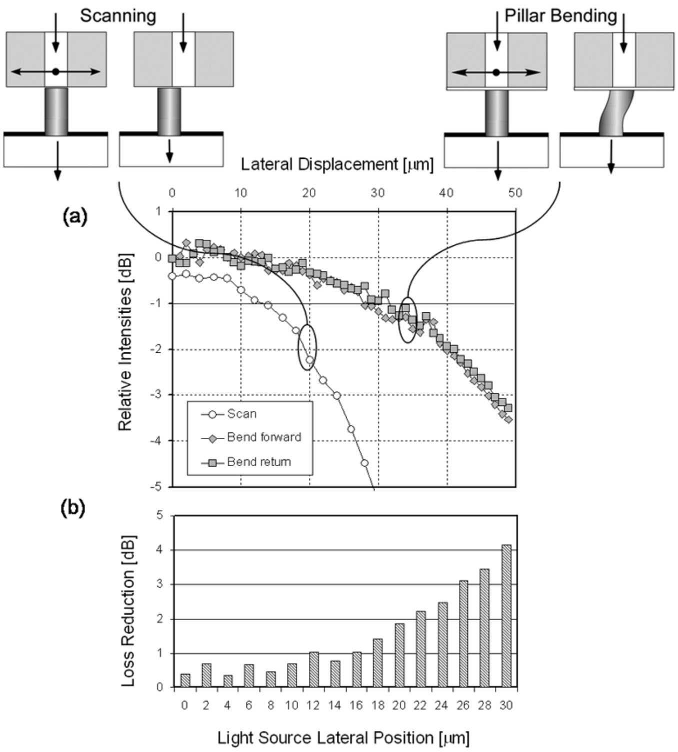

Fig. 5. (a) Relative transmitted intensities for the lateral displacement of the light source in the cases of scanning and pillar bending which are visualized in the insets. (b) Misalignment loss reduction by pillar bending obtained by subtraction of the bending and scanning curves from (a).

exceed 0.2 dB. In fact, at the perfect alignment position (0-μm lateral displacement), the loss is less than 0.1 dB. The uncertainty in the optical power loss measurements is approximately ± 0.1 dB. Thus, for the 50×150 μm pillars, the excess losses are essentially negligible at the center of the pillar. At ± 10-μm offset from the center of the pillar, the intensity losses are less than 5%.

The high flexibility of Avatrel allows the pillars to bend and stretch laterally which optically compensates for light source displacements with respect to the substrate. To quantify the pillar bending effect, two experiments are conducted in the same experimental setup (see insets to Fig. 5). In the first experiment, "scanning," the light source was scanned laterally along the top of a straight pillar. In the second experiment, "pillar bending," the same light source is attached with a thin optical polymer layer to the top of the pillar forming air-free contact between the optical fiber light source and the substrate. This configuration is equivalent to the pillar-assisted chip assembly shown in Fig. 1(b), where the pillar optically bridges the VCSEL and PD with the substrate waveguides. In the "pillar bending" case, the lateral displacement of the light source causes sideway movement (bending) of the pillar. The pillar helps to keep the light confined and, thus, deliver a greater fraction of the incident light to the detector.

Fig. 5(a) shows the relative transmission intensity plotted versus the light source lateral displacement in the X-direction for the "scanning" and "pillar bending" configurations. Since the pillar and light source have radial symmetry, the results in the Y-direction are identical to those in the X-direction. It is clear that the pillar bending range is limited by the elasticity of the pillar and its adhesion at the top and bottom surfaces. As shown in Fig. 5(a), the 50×150-μm pillar can bend 50 μm sideways. The optical transmission is measured during the pillar bending forward and also on its return to the original position showing no significant hysteresis. In device operation, the bending range will most probably be less than tested here.

At zero lateral displacement, the "bending" curve is about 0.2 to 0.3 dB higher due to the intimate contact of the optical fiber (air-free contact) minimizing the Fresnel back-reflection. Fig. 5(b) shows the loss reduction due to the use of pillar bending at different displacements of the light source. At displacements up to 15 μm, the loss reduction is less than 1 dB. The loss increases up to 4 dB at 30-μm displacement. As described in the introduction, the optical power loss can have a crucial effect on the BER of a digital system. Thus, a limited loss budget is allowed for system misalignment to maintain error-free operation. Fig. 5(a) clearly demonstrates that for a given loss budget, e.g., 1 dB, the 50×150 μm flexible pillars double the displacement tolerance from less than 15 to about 30 μm. The 4-dB pillar-assisted loss decrease at 30-μm displacement can easily reduce the BER by 10^4 or more.

III. Conclusion

Test chips with Avatrel pillars 150 μm in height and 50 μm in diameter were fabricated by direct photopatterning on glass substrates coated with metal-film open apertures for light transmission experiments. The characterization of the pillars shows that the air-free optical interconnections through the pillars result in an optical power loss less than 0.2 dB. The ability of the pillars to bend significantly improves the displacement tolerance of the assembled parts. The displacement tolerance is doubled from 15 to 30 μm in the case of the 50×150 μm pillars. Pillars with larger aspect ratios and smaller diameters can provide even higher displacement compensation in dense chip-to-chip OI modules.

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