Uneven Curing Induced Interfacial Delamination of UV Adhesive-Bonded Fiber Array in V-Groove for Photonic Packaging

M. A. Uddin, Hau Ping Chan, Member, IEEE, T. O. Tsun, and Y. C. Chan, Fellow, IEEE

Abstract—The common approach to attaching a large number of fibers to a guided-wave device is to fabricate a linear array using V-grooves. UV-curable adhesives are used to attach the fiber in V-groove for the fabrication of fiber array. Interfacial delaminations at the adhesive fiber interfaces are common after the reliability test due to uneven curing of the UV adhesive. This paper investigated the causes of uneven curing that gave rise to delamination. An analytical ray tracing technique was used to estimate the variation in light intensity or shadowing during the UV curing of adhesives. These effects were found to be very severe when the refractive index difference between the adhesive and the cladding materials is very large. Based on this study, it can be concluded that the delamination problem can be minimized by selecting a UV-curable adhesive having the same refractive index of the cladding material. It is also recommended to light illuminate from the topside for fiber packaging.

Index Terms—Bonding, delamination, fiber array, optical propagation, packaging, reliability, shadowing, V-groove.

I. INTRODUCTION

PACKAGING, and in particular pigtailting, is becoming an increasingly important issue as optical networks move from the wide area network (WAN) domain to the local area network (LAN) domain with a resultant pressure to increase production and reduce cost [1]. Fiber-to-waveguide connection is one of the key technologies in the realization of guided-wave optical devices [2]. A modified passive technique for higher port number devices is fiber arrays in V-groove blocks. It has been used in the precise alignment between fiber and optoelectronic devices [1]. The selection of appropriate bonding materials and method of attachment will determine the stability and reliability of the packaged device. Currently, UV-curable adhesives offer advantages in terms of mass productivity and low cost [3]. This type of adhesive not only performs the function of bonding but also has the high degree of light transmittance and other properties required to form a bond most suitable from the optics point of view. They can also be cured rapidly without affecting fiber alignment. Light curing also provides a number of economic advantages over the operations usually used. This includes rapid through-cure, low energy requirements, room temperature treatment, nonpolluting, and solvent-free formulations.

The adhesive is supplied in the form of reactive cross-linkable monomer blends, which polymerize on exposure to light radiation at an appropriate wavelength and power. Uniform adhesive curing and bondline dependence on the effective UV curing during adhesive curing. If there is uniform UV exposure, the interfaces will be drawn closer together creating very little stress. The uneven curing of adhesive in the package can generate high interfacial stresses upon heating or cooling of the structure during fabrication, assembly, or in field use. The propagation of the resulting delamination along an interface can degrade or destroy the functionality of the system [4]. Therefore, interfacial delamination, due to the uneven curing of adhesive, is one of the primary concerns in photonic package designs. Alignment and shrinkage of the fiber array also depend on the effective UV ray penetration during the adhesive curing process [5].

Due to the complexity of interconnects, it is also interesting to consider and study how UV light propagates through uneven interfaces. High light reflectance from any interface of the assembly reduces the light intensity for the next layer and induces uneven curing of adhesive. Shadowing due to light bending or optical element shape can also cause incomplete or uneven curing [6]. Very few studies have been directed to curing shrinkage and alignment of the fiber in V-groove: no attempt has been paid to the uneven curing induced by incompetent UV ray penetration. The previous study was performed to understand the origin of interfacial delamination in the adhesive fiber joint of a single V-groove by analyzing light reflection, transmission, and its intensity at different portions of the assembly [7]. However, the present studies elaborately described the details of the uneven curing-induced delamination of UV adhesive-bonded eight-channel fiber array. Only a clearer fundamental understanding of uniform light curing can allow manufacturers to develop highly reliable, low cost, and better performance optoelectronics products using UV-curable adhesive-bonded fiber array.

II. EXPERIMENTS

A. Materials

Fig. 1 shows the schematic of a typical cross-section of a fiber in V-groove. The fiber packages are made up of four different
materials: V-groove, fibers, adhesive, and pyrex lid glass. The V-groove is made of pyrex glass or silicon. Light can expose from both top and bottom sides of the pyrex V-groove, but it can expose only from the topside of the silicon V-groove. The size of the V-groove is appropriate for a fiber with a cladding diameter of 125 µm. The V-groove is symmetrical about a vertical plane, and the pitch is 250 µm.

The cladding and core material of the fiber are fused silica and 5 wt% GeO₂ (Germanium oxide)-doped fused silica, respectively. The refractive indexes of cladding and core material are 1.48 and 1.49, respectively. The adhesive is an epoxy-based polymer and supplied in the form of reactive cross-linkable monomer blends, which polymerize on exposure to radiation of an appropriate wavelength. In this study, three types of uncured UV adhesives were used with respective refractive indices of 1.40 (very low with respect to cladding material, n_clad = 1.48 for fused silica), 1.45 (slightly lower than cladding material), and 1.51 (slightly higher than cladding material), measured at a wavelength of 350–380 nm. The UV cutoff wavelength for the adhesives is 420 nm. Therefore, the transmittance of all adhesives is almost 100% in the used wavelength range (350–380 nm) of UV light for curing purposes. For the sake of discussion, they are referred to as Adhesive-1, Adhesive-2, and Adhesive-3, respectively. The viscosity of adhesive used in this experiment is about 1000 cps at 25 °C. The adhesives also found excellent properties at the initial characterization step in bonding two glass slides.

**B. Fiber Assembly**

Fig. 2 shows the schematic of the bonding process of an eight-channel fiber array. To prepare the fiber for placement into the V-grooves, it is stripped of its acrylic coating. The eight stripped fibers were inserted into the V-groove, and the lid glass was placed on them, seating them firmly into the V-grooves. After the fibers are seated, low-viscosity UV-curable adhesive is applied to the leading edge notch of the substrate. The adhesive wicks down the length of the V-grooves and underneath the fibers by capillary forces. Adhesive bonding occurs as a direct result of irradiation from a UV light source (EFOS N2001-A1 Novacure UV Spot Curing Light Source) for various curing condition (UV power, 1000–5000 mW/cm² and time of 10–120 s). The distance from the light guide output end to the target surface was 10 mm. The light guide position was such that it illuminated perpendicularly at the center of the fiber array. Upon curing, the fibers were permanently bonded into place. Fig. 3 shows the appearance of the bonded fiber packages on both silicon and pyrex V-grooves. However, this experiment has focused only on a pyrex V-groove, and comparisons were made between top and bottom side illuminations for different fiber locations in the fiber array.

**C. Reliability Study**

The test was performed according to the test procedure that satisfies the Bellcore requirements (GR 326-CORE). The samples were placed in an environmental chamber at 75 °C temperature and 95% relative humidity for 168 h. They were then removed from the test chamber and the end faces of the fiber were prepared by metallographic technique [8]. A scanning electron microscope (SEM) was used to investigate any delamination induced at the adhesive fiber interfaces.
III. RESULTS

At the initial material characterization step, the adhesive-bonded glass slide showed excellent results in shear strength and environmental test (no delamination), but after the reliability test of the adhesive-bonded fiber array, the SEM micrographs showed many delaminations at various locations with different extents. The delaminations are classified and summarized below according to location and extent.

A. Interfacial Delamination and Its Location

Fig. 4 shows the typical end face images of the delaminated fiber in V-groove for Adhesive-2. Inset shows the higher magnification photos of that delaminated location. The figure shows that the delamination is in the particular location, which is at the opposite side of the fiber from that light illuminated. When light was illuminated from top side, the delamination was found at the bottom side of the fiber [Fig. 4(a)]; on the other hand, when illuminated from the bottom side, it was found at the top side [Fig. 4(b)].

B. Extent of Delamination

Comparison between Fig. 4(a) and (b) shows the larger delamination when light illuminated from the bottom side due to the geometrical shape of the assembly. Again, the extent of delamination also varied from fiber to fiber of the array. Fig. 5 shows similar magnification of the end face images that clearly depict the extent of delamination for middle fiber and outermost fiber when light illuminated from the top side for Adhesive-2. It was lesser in the middle fiber [Fig. 5(a)] than the outermost fiber [Fig. 5(b)] of the same fiber array.

C. Effect of Refractive Index of Adhesive

The refractive index of the adhesive has great importance in case of fiber packaging. A larger delamination was observed for Adhesive-1 compared to Adhesive-2. Fig. 6 shows the comparison of delamination observed for two adhesives at the same magnification of outermost fiber when light illuminated from the bottom side. For Adhesive-3, the delamination was also found at a location other than those described for Adhesive-1 and Adhesive-2. As shown in Fig. 7, a delamination is observed at the outermost fiber when light illuminated from the top side.

D. Reason of Delamination

The delamination for different adhesives at identical and specific locations clearly indicates that it is not due to the adhesive problem, such as lower bond strength, cure shrinkage, or the stresses due to thermal mismatch. Those problems will introduce delamination at various regions of the package. In this case, delamination is certainly due to the lesser curing degree of adhesive at the delaminated region as a result of a drop in light intensity between the top and bottom sides of the fiber. The uncured or partially cured adhesives were more severely attacked by moisture during the reliability test. The bonding of uncured adhesive with water molecules reduced the adhesive strength and induced delamination on the interface. As a result, the adhesive detached from the fiber surface during the reliability test.

As the transmittance of the adhesive is almost 100%, there is no possibility of light scattering or absorption through the thin adhesive layer. The drop of intensity mainly occurs at the adhesive fiber interface in V-groove. Therefore, the following section has analytically investigated the main causes for
lies between 0.1 and 0.7%.

Fig. 5. End face images that clearly depict the extent of delamination. (a) At middle fiber. (b) At the outermost fiber when light exposed from the topside.

Fig. 6. Comparison of delamination observed at the same magnification of outermost fiber when light illuminated from the bottom side.

Fig. 7. Delamination for Adhesive-3 observed at the outermost fiber when light illuminated from the topside.

IV. THEORETICAL EXPLANATIONS

When light is incident on a boundary of two materials, part of the energy is reflected, part is absorbed, and part is transmitted. The optical absorption of a material is a function of its chemical and physical structure and varies with wavelength and thickness. It is expressed in terms of an absorption coefficient \( \alpha \) (also called absorption constant or loss coefficient) and defined by the relationship [9]

\[
\alpha = -\left( \frac{1}{t} \right) \ln \left( \frac{I}{I_0} \right)
\]

where \( I/I_0 \) represents the internal transmittance and \( t \) is the thickness. Table 1 shows the absorption coefficient of the cladding material (Fused silica) for different wavelengths [10]. The absorption properties of core materials (5 wt% GeO₂-doped fused silica) are also almost the same as that of nondoped silica, especially at lower wavelength [11]. From the calculated results, the maximum absorption loss through the optical fiber is only 0.01% within the UV range. Therefore, the effect of light absorption through the fiber could be neglected. The transmittance of adhesives is also almost 100% in the used wavelength range (350–380 nm) of UV light for curing purposes. Hence, in the following discussion, we only focused on the impacts of reflection and refraction to the delamination problem.

A. Uneven Curing Due to the Reflection of Light

The reflection loss at the interface of two materials depends on the incident angle and the refractive index difference between the two materials [12]. At the curved fiber surface, the
TABLE I
ABSORPTION COEFFICIENT FOR THE ClADDING MATERIAL (FUSED SILICA)

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Absorption coefficient (cm⁻¹)</th>
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<tbody>
<tr>
<td>300</td>
<td>0.010</td>
</tr>
<tr>
<td>350</td>
<td>0.005</td>
</tr>
<tr>
<td>400</td>
<td>0.002</td>
</tr>
<tr>
<td>500</td>
<td>0.001</td>
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</tbody>
</table>

radius of the circle acts as a normal axis. Therefore, parallel lights have different incident angles at different points of that surface. Fig. 8 schematically shows the variation of incident angle at different points of adhesive fiber interface during the parallel light illuminating from the topside of the V-groove. Due to fiber geometry, it varies from 0° to 90°. It is zero at point A, then increases gradually, and reaches its maximum value (90°) at points B and C. Light reflectance also varies with that variation of incident angle. The ratio of reflected to incident power can be obtained from [10]

\[ R = \left( \frac{n_1 \cos \theta_i - \sqrt{n_1^2 - n_2^2 \sin^2 \theta_i}}{n_1 \cos \theta_i + \sqrt{n_1^2 - n_2^2 \sin^2 \theta_i}} \right)^2 \]

where \( n_1 \) and \( n_2 \) are the refractive index of the first and second medium, respectively, and \( \theta_i \) is the incident angle of light.

Based on the above equation, Fig. 9 shows the variation of light reflectance with the incident angle for three adhesives. Initially, light reflectance increases very slowly with the increase of incident angle and then rises more rapidly above the incident angle of 70°. The result also shows that the reflectance is higher for a large value of \( \Delta n \), which is the refractive index difference between adhesive and cladding materials. Therefore, reflectance is much higher for Adhesive-1 than that of Adhesive-2. For Adhesive-3, reflectance increases significantly above an incident angle of 60° and becomes 100% at or above the incident angle of 78.5° due to total internal reflection.

Fig. 8 clearly shows the large incident angles (more than 70°) close to points B and C, near the fiber V-groove contact point. Light reflectance is very high for this large incident angle. By conservation of energy \( R + T = 1 \), what is not reflected is transmitted (no absorption is assumed). In tracking the flow of energy through reflection and transmission, it is realized that light striking a surface at an angle has less intensity—less joules landing per unit area—than light striking normally (head-on). Therefore, transmittance decreases with the increase of incident angle. Initially, it also decreases very slowly for a lower incident angle and then dropping more rapidly as the incident angle approaches 90°. Low intensity lands up in this region and the adhesive remains partially uncured. Differences in intensity at different portions of the adhesive cause uneven curing. When light illuminated from the bottom side of the V-groove, it resulted in the same condition as light illuminated from the topside.

B. Uneven Curing Due to Shadowing

When light was incident on a curved surface from light medium (adhesive) to dense medium (fiber) with a large incident angle, shadowing resulted in the denser medium due to light bending toward the normal axis. The following is a mechanism of the shadowing at the curved optical fiber surface. Fig. 10(a) and (b) schematically shows the shadowing mechanism for fiber in a V-groove when the light is illuminated from the top and bottom sides, respectively.

When the light ray is incident at a location slightly away from either point B or C of the fiber, it would pass through directly without any refraction, as it does not experience any medium change along its propagation. Moreover, when a light
C. Variation of Shaded Area

The shaded area was determined by ray tracing for different incident and refracted rays. Fig. 11 schematically shows the ray tracing method for the determination of shaded areas when light illuminates from the bottom side [13]. Then, it was calculated by coordination geometry \((x, y)\). A larger shaded area was observed for Adhesive-1 compared to Adhesive-2. Table II shows a comparison of minimum and maximum shaded area at the middle and outermost fibers between Adhesive-1 and Adhesive-2. When light illuminated from the topside, the shaded areas were observed at the bottom side of the fiber (two spots). On the other hand, shaded areas were observed at the topside between fiber and pyrex lid glass (also two spots) when light illuminated from the bottom side. A larger shaded area was also observed when illuminated from the bottom side due to the geometrical shape of the assembly. The above condition was only for parallel light incident vertically on the adhesive fiber interface, but in the actual case, the light is incident on this interface with slight inclination and varies from fiber to fiber. Fig. 12 schematically shows how light inclination varies with vertical axis, which affects the incident angle on fiber surfaces. At the outermost fiber, the incident angle on a pyrex lid glass is larger than any other fiber. Therefore, light inclination on the adhesive fiber interface with vertical axis is also larger at the outermost fiber. Consequently, the incident angle and light reflectance are also higher at the outermost fiber and lower at the middle fiber.

The calculated results show that a vertically incident light gives a minimum shaded area than any inclined light on that surface. The minimum shaded area is observed at the middle fiber, where light is incident almost vertically on the fiber surface and maximum at the outermost fiber, where the incident light makes the highest inclination with the vertical axis. Fig. 13 shows the variation of total shaded area (two spots) within the single V-groove for different fibers of the eight-channel fiber array for light illuminating from top and bottom sides. The figure shows that the shaded area increases gradually from middle fiber to outermost fiber.

D. Induced Delamination Due to Uneven Curing

The shaded part remains unexposed to UV and the adhesive remains uncured. Surrounding the shaded area, though light is exposed, its intensity was also very low, because the light was approached here by a large incident angle (above 70°) with a huge loss of intensity due to higher light reflection from the adhesive fiber interfaces. The photo-curing kinetics states that the more light intensity falls on the sample, the higher the conversion [4]. Therefore, adhesives surrounding the shaded area were also partially uncured. Those unexposed or uncured adhesives were more severely attacked by moisture during the reliability test. Such a hydrolytic attack breaks the ester linkages \((R - (C = O) - OR)\) of polymer chain and creates two new end groups: a hydroxyl and a carbonyl [14]. Hydrolyization of the adhesive would appear to weaken its mechanical strength and adhesion with glass. The reduced adhesive strength induced delamination on that interface. As a result, the adhesive
detached from the fiber surface during the reliability test. Fig. 14 shows high-magnification SEM images that depict how this adhesive segregates from the optical fiber surface.

For Adhesive-3, the shaded area is also removed, because light entered from a denser medium and bent away from normal, but light intensity greatly differs between the top and bottom sides due to the total internal reflection from some parts of the optical fiber surfaces. Therefore, the adhesive remains partially uncured and induced internal stress and delamination during the reliability test. However, the delamination is at a place (Fig. 7) other than described before for Adhesive-1 and Adhesive-2.

Comparison of Figs. 4 and 10 shows that the positions of the shaded area obtained from analytical results are exactly the same as the delamination found from the reliability test. The larger shaded area obtained from analytical results also confirmed the greater extent of delamination when light was illuminated from the bottom side. Comparison between Figs. 5 and 13 shows that the extent of delamination at different fibers also varies according to the shaded area. Again, the comparison between Figs. 6 and 13 shows that the extent of delamination also varies according to different adhesives. Thus, the analytical results fully established the reason of uneven curing for the delamination of reliability studies. When light was exposed from both sides to remove the shaded area, it disappeared, but high-intensity variation certainly induced greater internal stress at the interfaces and can also damage (photo degrade) the cured material [4].

### TABLE II

**Comparison of Minimum and Maximum Shaded Areas at the Middle and Outermost Fibers Between Adhesive-1 and Adhesive-2**

<table>
<thead>
<tr>
<th>Adhesive (Refractive index)</th>
<th>Calculated shaded area (μm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Illuminated from top side</td>
</tr>
<tr>
<td></td>
<td>Middle fiber</td>
</tr>
<tr>
<td>Adhesive-1 (1.4)</td>
<td>48</td>
</tr>
<tr>
<td>Adhesive-2 (1.45)</td>
<td>14</td>
</tr>
</tbody>
</table>

V. Conclusion

Due to the circular shape of the optical fiber, parallel lights make different incident angles on different points of the fiber surface. At some points on the adhesive fiber interface, light reflectance is very high as a result of a large incident angle. Therefore, light intensity differs between the top and bottom sides of the fiber. This difference in intensity introduces uneven curing of the fiber array. Moreover, light bending toward normal retains some shaded region in the adhesive layer. In this region, the adhesive remains uncured and causes delamination or distortion of the fiber array in the V-groove. The shaded area was calculated separately for light illuminating both from
the top and bottom sides. The minimum shaded area and the delamination was found at the middle fiber when light illuminated from top side. These were larger when light exposed from bottom side and maximum at the outermost fiber. This is due to the geometrical shape of the bonding element. These effects are very severe for a large value of $\Delta n$, which is the refractive index difference between adhesive and cladding materials. Based on this study, the delamination problem can be minimized by using the UV-curable adhesive having the same or slightly higher reflective index than that of the cladding material. From this study, it is recommended to expose light from the top side for fiber packaging. This type of fiber array will result in more reliable assembly and also increase the productivity of the fiber-optic industry.

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Hau Ping Chan (M'95), photograph and biography not available at the time of publication.

T. O. Tsun, photograph and biography not available at the time of publication.

Y. C. Chan (M'85–SM'95–F'04), photograph and biography not available at the time of publication.