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Failure analysis of adhesive bonded planar lightwave circuit (PLC) based optical splitter packages

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Failure analysis of a device has an important part to play in determining the causes of device failure and ways for making and using the devices to achieve greater reliability. Therefore an investigation was carried out for failure analyzing of adhesive bonded optical splitter packages using thermal cycling as an acceleration method. An optical splitter module simply composed of Y-branching waveguide devices on a substrate connected to and from optical fiber. However, it requires a lot of different materials with different properties to package such optical splitter in a case. As the thermo-mechanical properties of these different materials are normally quite different among each other, the thermal stress is induced due to the variation in coefficient of thermal expansion (CTE), hence affecting the optical performance and long-term reliability of the device. Therefore, an investigation was carried out to study the effect of housing on the reliability of adhesive bonded optical splitter modules with reference to the Telcordia requirements. A significant degradation in performance was found for the packaged splitter in housing during thermal cycling test. This is mainly due to the stress-induced misalignment effects between the PLC chip & coupling fibers, and also fiber bending in the housing. The finite element method (FEM) was then employed to confirm of the experimental findings. This study can provide important dictation in the reliable packaging of optical splitter with minimizing the CTE mismatch effects.

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Keywords: Optical splitter, Adhesive bonding, Reliability, Thermal cycling, Coefficient of thermal expansion (CTE) mismatch, Insertion loss

1. Introduction

The rapid & global spread of the internet & multimedia communications has accelerated the growth in optical communications networks and there is an increase in demand for fiber-to-the-home (FTTH) optical access networks due to its huge capacity, small size, lightness and immunity to electromagnetic interference of optical fibers [1]. Planar lightwave circuits (PLC), can provide various key practical devices for such optical networks because of their suitability for large-scale integration, long-term stability, and mass-producing capability [2]. For example, optical splitter can branches and couples waves without converting optical transmissions into electric signals for connecting households to telecommunication carrier in optical communication networks. In order to utilize the integration capability of PLC devices, the input and output fibers have to be connected to PLC's. The fiber connected splitters are required to exhibit not only high optical performance such as low loss, wavelength flatness, low polarization dependence, but also long-term reliability. However, to attain a reliable low loss splitter, connection methods must be precise and meticulous [3].

There are three typical methods which are used to connect a fiber with an optical device. They are soldering, laser welding and adhesive bonding. The selection of a particular methods depends on a series of criteria, which include reliability, temperature excursions of subsequent packaging processes, package materials used, and the constraints imposed by active alignment and automated assembly. Therefore, the selection of appropriate connecting materials and method of attachment are very important in determining the stability and reliability of the packaged device. Soldering is a process by which two metal surfaces are bonded together by means of an intermediary alloy. Because of its metallic strength, the solder will offer a much better thermal stability against creep. Laser welding is a process that joins different parts by employing the heat generated by a laser beam directed onto the weld joint. The ability of laser welding with repeatable submicron precision distinguishes it from other forms of bonding technologies. However, they need metallization before bonding and thus increase the manufacturing cost of the components.

Currently, adhesives offer advantages in terms of mass- productivity and low-cost [4]. This type of adhesive not only perform the function of bonding, but also have the high degree of light transmittance and other properties required to form a bond most suitable from the point of optics view. They can also be cured by both thermal and light curing without affecting the fiber alignment. Light curing also provides a number of economic advantages: rapid through-cure, low energy requirements, room temperature treatment, non-polluting and solvent free formulations. In this way other heat sensitive materials in the assembly are not damage by the heat [5].

Fig. 1(a) and (b) shows the typical schematic configuration of unpackaged and packaged PLC-type optical splitter respectively. An unpackaged 1x8 PLC optical splitter simply included a PLC (splitter) chip, single-channel (input) and 8-channels (output) fiber arrays. The three parts are mounted by adhesive as shown in Fig. 1(a). However, in a packaged device, the mounted optical splitter is secured in housing by applying fixing adhesive between the Al fixing blocks and the fibers. Moreover, an adhesive is used to bond the rubber boots and the end of Fiber Arrays in the housing as shown in Fig. 1(b). It is very clear that different type of adhesive is needed for bonding different part of the PLC packages. In fact, a large number of different materials are ultimately required for assembling the splitter packages. The properties of these different materials are usually quite different among each other [6]. Therefore, it is very interesting to study how the different materials behave under the conditions of harsh environment [7]. For example, when the temperature changes in a material, it would expand/compress and this thermal induced expansion/compression is directly proportional to the coefficient of thermal expansion (CTE) of the material, its length and the temperature change. However, as the components & parts are rigidly connected and, thus, forced to expand in an identical manner. As a result, each part will impose a force along the interface on the other parts and cause stresses to appear [8].

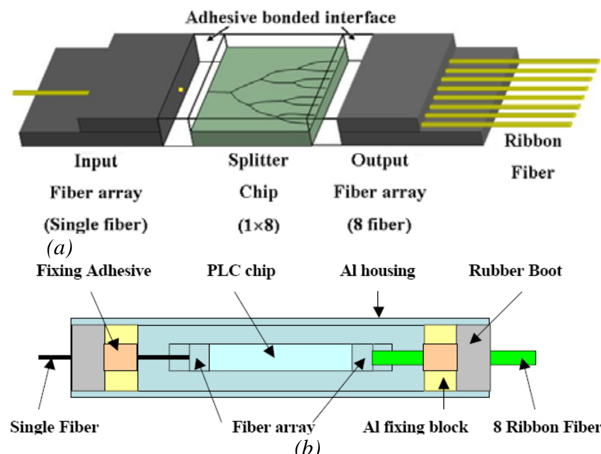


Fig. 1. (a) The schematic configuration of unpackaged PLC optical splitter; (b) The schematic configuration of packaged PLC optical splitter.

The CTE mismatch effect in the splitter package can generate thermal stresses upon heating or cooling of the structure during fabrication, assembly, or in field use. The generated thermal stress along with bending of fiber or components can degrade or destroy the functionality of the systems [9]. Therefore, the CTE mismatch among the materials of the component is one of the primary concerns in photonic package designs [10-11]. Our recent work shows that during the spinning under the influence of centrifugal forces & convectively driven evaporation, the material properties changes and degraded during the patterning process.

However, the problems related CTE mismatch effect to optical splitter performance has not been well studied. In this study, 1x8 PLC-type optical splitters were used to demonstrate the problems of CTE mismatch on the performance of packaged splitter device. Thermal cycling test is employed to evaluate the reliability, as it is a most effective method to investigate thermo-mechanical behavior caused by CTE mismatch effect. Experimental and numerical simulations are carried out to investigate the problems related to CTE mismatch in adhesive bonded optical splitter packages. Only a clearer fundamental understanding on the CTE mismatch effect can help in the development of more reliable adhesive bonded optical splitter packages.

2. Experiments

A 1×8 PLC optical splitter mainly included a PLC (splitter) chip, single channel (input) and 8 channel (output) fiber array. Therefore, the experimental works are divided into subdivision and described accordingly.

2.1 Fabrication of fiber array

Fiber array acts as an effective coupling media to launch the optical signals in and out the port of a PLC chip. Without fiber array it is very difficult to align the individual fiber to the corresponding input/output port of the chip. It is made by anchoring optical fiber(s) on precision engineered V-groove(s). Fig. 2 shows the schematic of the bonding process of 8 channel fiber array. The details on the fabrication of fiber array are discussed in our previous studies [5, 7].

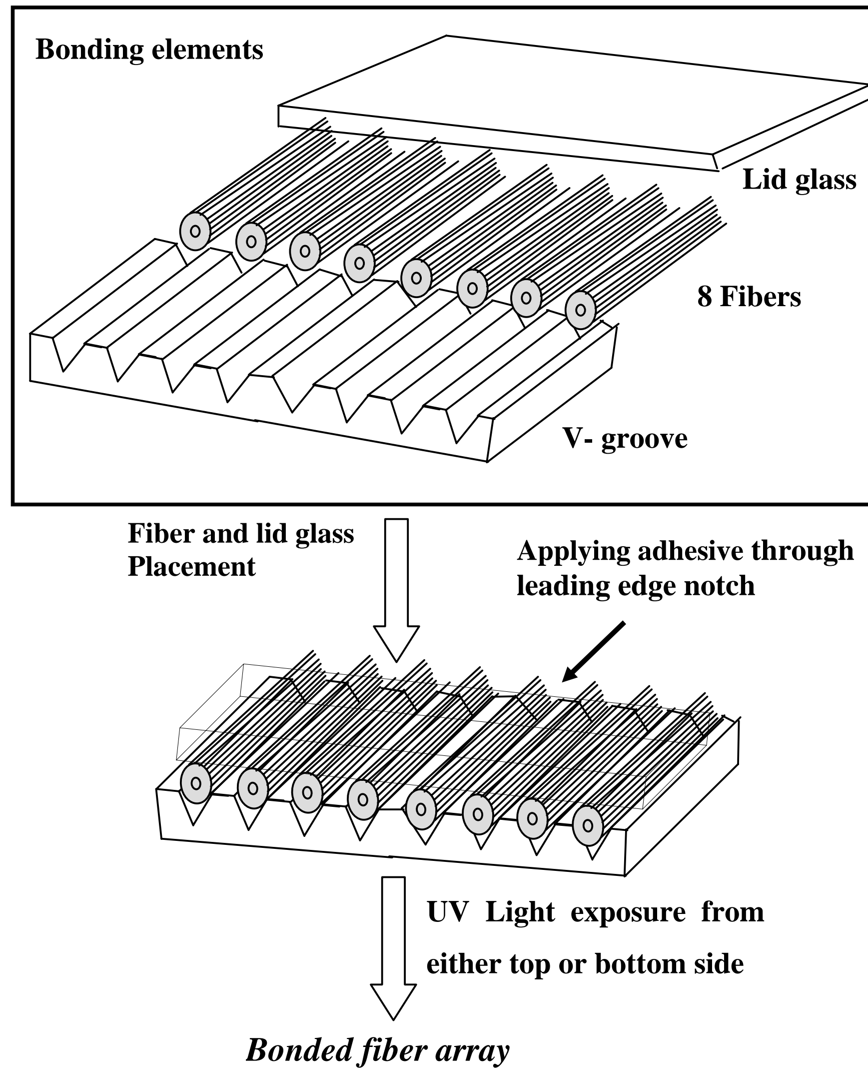


Fig. 2. Schematic of bonding process of 8 channel fiber array.

2.2 Fabrication of silica- based PLC waveguides

Silica- based PLC splitter chips were fabricated on quartz substrate with conventional PLC technology consisting of FHD (Flame hydrolysis deposition) and RIE (Reactive Ion Etching) techniques. In FHD process the under cladding and core was formed by deposition of fine glass particles or soot chemically produced in an oxy-hydrogen flame on quartz substrate. After deposition, the substrate with these two porous glass layers is heated to about 1300°C for consolidation, and the glass particle layers become transparent glass layers [12-14]. The waveguide core ridges are then defined by a Photolithography [15-16] technique and unwanted potions of the core region are removed by RIE. The core ridges is covered with an over cladding again by FHD.

2.3 Packaging of PLC optical splitter

Packaging of optical splitter is mainly performs in two steps, aligning the components and adhesive bonding.

2.3.1 Alignment procedure

In the alignment process of PLC module, splitter chip and fiber arrays are mounted on the respective holders of automatic alignment machine. The input side of PLC chip was coupled to single fiber array, and the output side was

coupled to ribbon (8-channel) fiber array. A laser source is used to launch the optical power into input port of splitter chip through the input fiber array, and the power output from the splitter chip through the output fiber array are detected by the power meter. With reference to the optical power signals, the positions of the I/O fiber arrays are adjusted and aligned automatically by auto alignment machine. Since the core diameter of the fiber and waveguides are within a few microns, they should be accurately aligned to achieve a low insertion loss.

2.3.2 Adhesive bonding

When the optimal position is achieved, the fiber arrays are bonded to the ends of the splitter chip using UV curable adhesive. Finally the PLC module is secured in the housing by applying a fixing adhesive between the fixing blocks and the fibers. Aluminum housing is traditionally used as low cost one in typical photonic packaging [6]. The UV curable adhesive thickness has to be kept small in order to minimize the variation of connection loss due to thermal expansion of the adhesive. This can be achieved by pushing the fiber array and PLC together during the curing process. The dimension of housing in our case is 6 x 8 x 55 mm. Fig. 3 shows the appearance of a bonded PLC optical splitter packages in an aluminum packages.

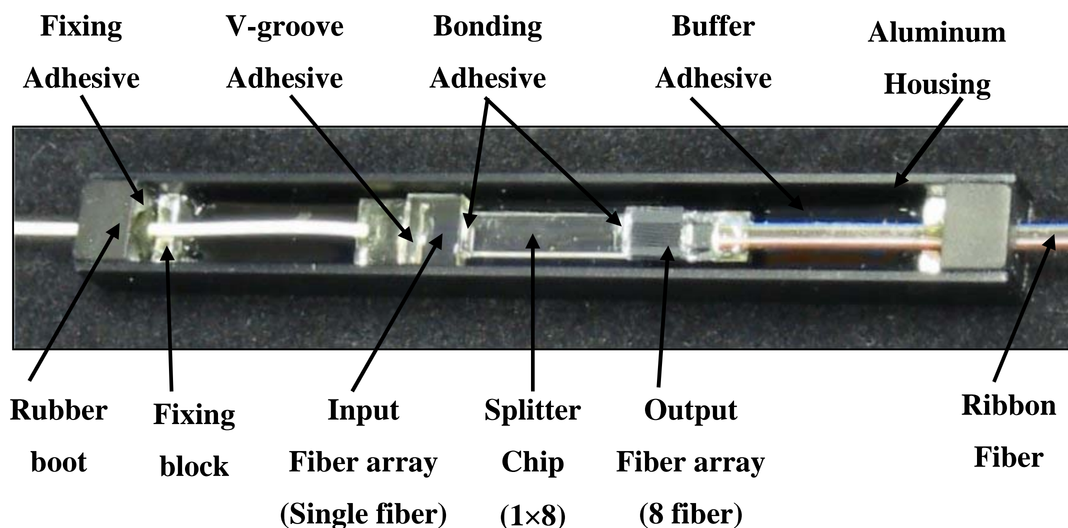


Fig. 3. Appearance of a bonded PLC optical splitter packages in an aluminium packages.

2.4 Reliability test of optical splitter

According to the Telcordia standard, thermal cycling test (TCT) was employed to evaluate the thermo-mechanical behavior in 1x8 PLC-type optical power splitter packages. The test condition of TCT was changed from –40°C to 85°C, with 1°C/min ramp rate and 30 minutes dwell time. Insertion loss (I_L) is one of the most important parameter to determine the optical performance of passive optical splitter [7, 17-18]. The I_L was measured at room temperature and at both extreme temperatures during thermal cycling test at 1.5μm wavelength by an optical loss analyzer. In order to investigate the effect of the housing on the insertion loss, two types of samples were tested under TCT. The first type of sample was unpackaged one as shown in Fig. 1(a), whereas the later one was packaged with aluminum housing as shown in Fig. 1(b). In this case, a discrepancy in the performance between the samples was mainly due to the aluminum housing. To achieve the highest measurement accuracy, all the fibers were connected by splicing instead of optical connectors. The repeatability of the loss measurement setup was better than 0.05dB. For the sake of analysis, ΔI_L was defined as the I_L different between the extreme temperatures and its nominal values (25°C).

3. Results and discussion

The packaged PLC based optical splitter is composed of many materials with different properties. Table 1 shows the physical properties of materials used in the packages.

Table 1. Physical properties of packaging materials.

Description	Material	CTE (ppm/^{o}C)	Modulus (PSI x10^6)
Fiber	Fused silica	0.55	10.500
Fixing adhesive	UV cure epoxy	68	0.100
Bonding adhesive	UV cure epoxy	55	0.100
V-Groove adhesive	UV cure epoxy	55	0.100
Rubber Boot	Silicone	150	0.005
Housing/fixing block	Aluminum	24	10.007
PLC chip	Quartz	0.55	10.500
Fiber Array substrate	Pyrex	2.60	21.750

The different coefficient of thermal expansion (CTE) would induce different dimensions of elongations or contractions in material bonding interfaces when experiencing temperature variation. As a result, significant stresses would produce, which also would induce the misalignment between the PLC chip and the coupling fibers, causing a significant degradation in performance. However, for such PLC devices to have any practical use in optical access network, the variation of insertion loss against temperature has to be kept as small as possible. The insertion loss of a typical optical power splitter with packaged and unpackaged at both extreme temperatures (–40°C and 85°C) were measured. It is found that during thermal cycling test at extreme temperatures, the insertion loss deviates from its nominal values (25°C). The measured ΔI_L for each output channel for packaged and unpackaged sample at -40°C and 85°C were as shown in Fig. 4(a) and (b) respectively. It can be observed that at extreme low temperature (-40°C), the ΔI_L for packaged sample increased 0.5dB more than unpackaged sample. However, ΔI_L for packaged sample increased slightly at 85°C. This is mainly due to CTE mismatch effect. The important facts of the results are discussed as follows.

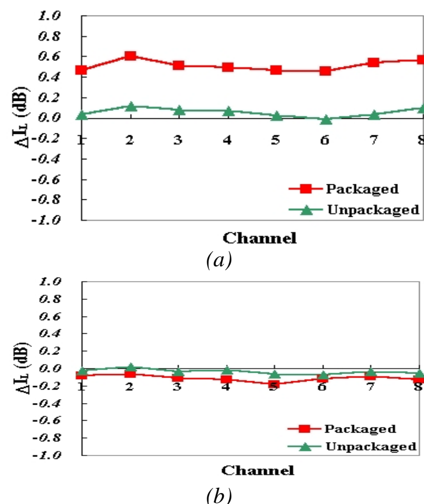


Fig. 4. (a) Delta insertion loss (ΔI_L) of packaged and unpackaged sample at –40°C; (b) Delta insertion loss (ΔI_L) of packaged and unpackaged sample at 85°C.

3.1 Higher insertion loss in packaged optical splitter than unpackaged one:

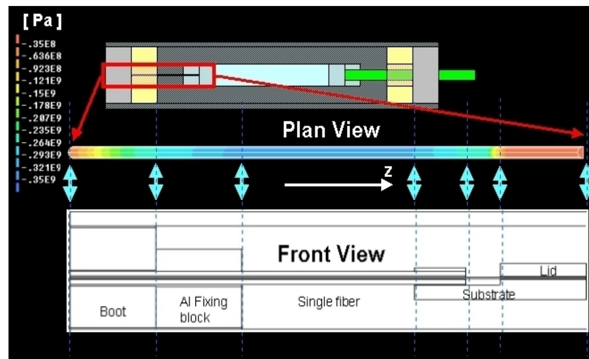
Different materials in the packaged device are expanding and contracting accordingly to different dimension when experiencing temperature variation. These caused significant residual thermal strain and thermal stress during thermal cycling test at the interfaces. For example, the CTE of aluminum housing is almost 40 times larger than that of fiber material (fused silica) and PLC chip materials. Therefore, at both extreme temperatures (-40°C and 85°C), the delta insertion loss is higher for packaged splitter than the unpackaged one. In an unpackaged optical splitter, there is no aluminum housing and rubber boot. Thus, the CTE mismatch induced stress can relax and the delta insertion loss was almost unchanged. However, in the packaged device, the elongation/contraction rate of aluminum housing is almost 40 times higher than that of fiber and chip materials. As a result, the CTE mismatch induced stress cannot release and ultimately increased the insertion loss of the packaged splitter.

3.2 Larger deviation at extreme low temperature (–40°C) than high temperature (85°C)

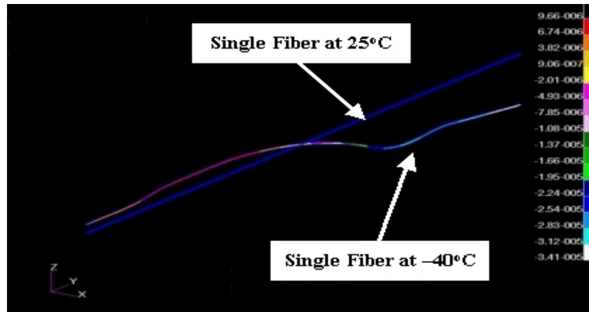
The delta insertion loss of the packaged optical power splitter was about 0.5dB at –40°C and only -0.15 dB at 85°C. At higher temperature (85°C) the aluminum housing expands 40 times more than the fiber, inducing tensile strain to the fiber. As a result, the fiber becomes straighter within the package. As no compression force or fiber bending exhibits in the packaged optical splitter at high temperature, the ΔI_L of packaged splitter remains more or less the same. However, at lower temperature (-40°C), aluminum housing exhibit CTE contraction 40 times larger than the fiber. However, the stiff optical adhesive layers prevent relative motion between the fiber and the aluminum housing, so a very significant compressive stress was exerted along the fiber, causing fiber bending. This fiber bending significantly increased the I_L of packaged optical power splitter at lower temperature (-40°C).

3.2.1 Fiber bending during thermal cycling of packaged optical splitter at low temperature (–40°C)

Since the CTE of aluminum is almost 40 times higher than that of the fiber materials, aluminum housing exhibit CTE contraction 40 times larger than the fiber at lower temperature. However the packaged is fixed by the optical adhesive. So a very significant compressive stress was exerted along the fiber, causing fiber bending. The fiber bending in the packaged devices were analyzed by thermal stress modeling using PHYSICA software. The schematic diagram on single fiber side and the FEM results of fiber bending induced by CTE mismatching along the single fiber were as shown in Fig. 5 (a) and (b) respectively.



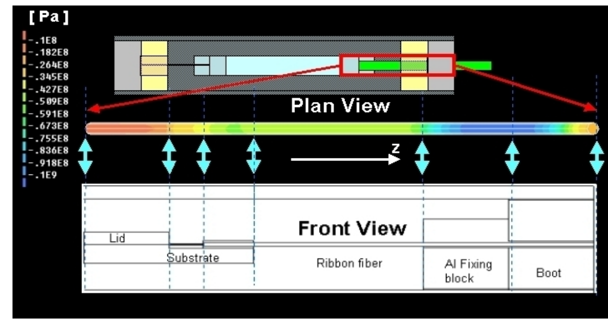
(a)



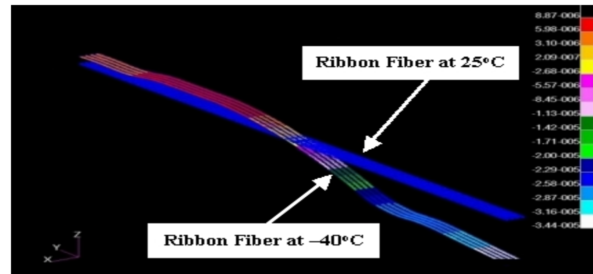
(b)

Fig. 5 (a): Schematic diagram of single fiber side; (b) FEM results of fiber bending along single fiber.

The schematic diagram on ribbon fiber side and the FEM results of fiber bending induced by CTE mismatching along the ribbon fiber were as shown in Fig. 6 (a) and (b) respectively. Thus compressive stress induced fiber micro bending in splitter package, causing insertion loss increased at low temperature under thermal cycling test.



(a)



(b)

Fig. 6. (a) Schematic diagram of ribbon fiber side; (b) FEM results of fiber bending along ribbon fiber

3.2.2 Bending loss

The bending loss due to fiber bending with R_c (Radius of Curvature) can be determined from power transmission coefficient T, which is expressed by the following equation [11]

$$T \cong 1 - \left(\frac{a}{R_c}\right)^2 \left(\frac{\omega}{a}\right)^6 \frac{V^4}{8\Delta^2} \qquad (1)$$

where a, ω, V and Δ are the core radius, spot size, normalized frequency and refractive index difference of the fiber respectively. It can be noted that the bending loss of the fiber depends on the value of R_c. So if there is no fiber bending, R_c will be infinitive, T will become 1, i.e., 0dB loss. On the other hand, if by any means, there is a fiber bending, R_c will be become finite, T will be less than 1. It is very difficult to quantitatively measure the bend radius in practice, but any increases in bend radius can always results an increase in the insertion loss.

3.2.3 Fiber cracks in temperature cycling test

As mentioned in previous section, the CTE mismatch effect induced fiber bending in packaged PLC optical splitter, which significantly influenced the ΔI_L during thermal cycling.

Moreover, the fiber jacket of input and output fiber array was stripped for V-groove alignment in fiber array assembly. These caused a part of bare fibers directly explore without any protection, which may influence the long–term thermo-mechanical reliability for the device. Accordingly, cracks are found in the packaged PLC optical splitter after the temperature cycling test. The cracks are easily observed under optical microscope and shown in Fig. 7. From the numerical calculations, it is found that the absolute maximum compressive stress along the single fiber and ribbon fiber were 345MPa and 148MPa respectively. The large amount of compressive stress often initiate the fiber cracks in the single fiber of input fiber array.

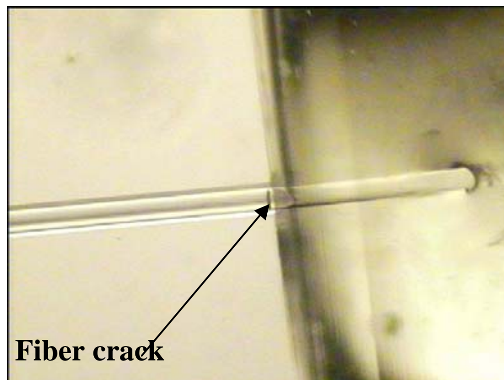


Fig. 7. Fiber cracks on the side of input fiber array

From this study, it can be proposed to use low CTE materials such as stainless steel for housing in the packaging of PLC type optical splitter. However, need to add extra cost for expensive stainless steel housing. Another alternative is using the moveable rubber boot to minimize the expansion or contraction induced stress. However, the package can not be made totally hermetic to protect from environmental degradation.

4. Conclusions

The reliability of adhesive bonded PLC based optical splitter packages is studied. The effect of CTE (coefficient of thermal expansion) mismatch on the performances of optical splitter was investigated. Insertion loss (I_L) was measured in accessing the optical performance of the components. The thermal cycling from –40°C to 85°C is used as the reliability study. The comparison was made between the packaged and unpackaged optical splitter. In an unpackaged optical splitter, the CTE mismatch induced stress can relax and insertion loss was almost same. However, in the packaged device, the stress cannot release and increased the insertion loss. It is found that for the packaged sample ΔI_L increased to 0.5dB at -40°C, while ΔI_L increased slightly at 85°C. The CTE mismatch effect also induced fiber bending inside packaged which ultimately initiate the fiber cracks. Moreover, the numerical simulation has been used to confirm the experimental results and interpretation. These numerical calculations were in good agreement with the experimental measurements. These results can be also applied on many PLC based optical device packages to minimize the CTE effects.

Acknowledgements

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