Optical splitters are key elements in passive optical networks. Fused couplers with standard packaging techniques are not “well-reliable” for harsh outside plant environment. Field failed coupler samples are analyzed to understand the failure modes of couplers in the outside plant environments. Based on experimental studies, an improved packaging process for fused coupler is proposed. Couplers with the new design are fabricated and long term stability is evaluated, which shows an improvement in performance over conventional coupler designs.
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Passive Optical Network (PON) guarantees superior performance with reduced maintenance cost and flexibility to deploy anywhere without power availability. Splitter Array Sub Assemblies (SASAs) are the most critical elements in Fiber-To-The-Home PON deployments. SASAs help to distribute the signals evenly to multiple ports, and share the cost of fiber plant among multiple customers, making PONs a promising solution for today’s access networks [1]. The performance quotients of splitters are stated on low excess loss, wavelength independence and good uniformity. Along with these performance specifications, long term performance stability and reliability is equally important for SASAs, which call for reliable and efficient packaging techniques.

Recent developments in wavelength insensitive fused monolithic 1xN couplers has regained the importance of fused coupler based SASAs, as they can offer high uniformity couplers and high port count couplers. Even though these products meet performance and reliability specifications, they could still suffer from performance degradation and even failures in the field. Thus it is very important to analyze the field failure mechanisms in such couplers, to offer zero defect system performance over the expected service life. This chapter describes our studies on the failure modes of fused couplers and the various packaging schemes to improve its performance towards impact and long term stability.

7.1 Basic Packaging Method

In all-fiber components, the constituent material is silica glass in the form of a hair-thin structure. Packaging plays a key role for their deployment in the field and long-term stability. Besides, for fused coupler components, because of the nature of their fabrication, the physical structure and optical characteristics of the glass fibers are modified. As a result, the component becomes susceptible to all known sources of weakness associated with the fused bare fiber. A suitable package is, therefore, required to preserve optical properties against the effects of mechanical and environmental stresses. Packaging protects the component after its realization for a reliable operation in the field [2].

Since the fibers used in fabricating FBT couplers are stripped off the protective coating, and the fused region is tapered to very thin (~ 40µm) fragile structure, the device is extremely sensitive to ambient conditions [3]. This often leads to waist breakage of the device near its centre portion unless it is suitably protected. In order
that the physical structure and device properties, such as excess loss and the splitting ratio of the coupler component are not affected by the package, some essential requirements are to be satisfied. The device after fabrication should be kept suspended under uniform tension from either side in order to get rid of any bend or twist in the waist region. Any minute distortion in the taper shape can cause a large change in the splitting ratio [4, 5, 6] and degrades the loss performance of the device [7, 8]. The packaging substrate must not touch the device anywhere in the tapered region in order to avoid any refractive index modification of the outer surface of the taper [9, 3]. The physical contact can also transmit heat surrounding the device by conduction, which may result in variation of the splitting ratio [10, 11]. The device along with the substrate, in the final packaged form should be sealed air-tight in a tube to avoid any exposure to moisture or dust particles, which otherwise may seriously degrade the performance of the device.

Out of the various packaging schemes of standard FBT components [12], the quartz substrate packaging appears to be very reliable and most widely accepted. The package involves a two-stage protection – the primary package and secondary/outer protection. Primary packaging provides the inner layer of protection for the device (Figure 7.1). The material properties of the primary packaging substrate have a large influence on the performance of the device because of the variations in the thermal...
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and environmental conditions. The best choice for the material of the primary package is quartz since it exhibits the same behaviour as of the fiber. As shown in Figure 7.1, the substrate is semi-cylindrical with rectangular groove, which can be easily positioned and fixed by a 3-dimentional micro-positioner from underneath the fabricated fiber-device and fixed at the ends using a suitable adhesive. In this investigation, quartz substrates with a length of 47mm and with a groove dimension of 1000x600 μmxμm, is used.

After primary packaging, the device is still bare and needs to be further encapsulated for protection. The device with the primary package is inserted into a metal tube and is shielded at the ends by sealants to keep it air-tight. Invar, a metal alloy that has approximately the same coefficient of thermal expansion as that of silica is used. Care is taken to mount the two ends of the packaged device with the emerging fiber leads such that the package should withstand stress/twist (and stability of the device characteristics) during handling and installation.

7.2 Failure Modes in Fused Couplers

Even though couplers are subjected to standard accelerated tests to simulate the service life in the field, they experience occasional performance degradation and even failures during installation or service. These field problems can cause undesirable service interruption and financial liabilities to the service providers. Field failed samples are cut open and studied for their morphology, structural integrity, surface problems etc. Different techniques such as Optical Microscopy and Scanning Electron Microscopic (SEM) were suggested to analyze the defects [13]

Slow drift in coupling ratio at 85°C and 85% relative humidity is one of the long term failure mechanisms in fused couplers [14]. Optical adhesive instability at high temperature and humidity is reported as one of the reasons for this drift [15]. Direct diffusion of molecular water (or possibly OH) into the optical fiber can cause coupling ratio drift [14]. As water enters the fiber, the refractive index of the silica decreases, causing an increase in the coupling ratio. Diffusion of water into the coupling region occurs from the humidity chamber. The concentration of water C(r,t) in a cylinder of radius b, with a constant external concentration C₀ and initial internal concentration of zero, as a function of time t and radial position r is given by:

\[
C(r,t) = C_0 \left( 1 - \sum_{n=1}^{\infty} B_n J_n(j_n r/b) \exp\left[-j_n^2(DH_2O(T)t)/b^2]\right) \right) \quad (7.1)
\]
where

\[
B_n^2 \equiv \frac{2}{\left[J_n J_1 (j_n)\right]} \quad (7.2)
\]

\(J_n\) is the \(n^{th}\) Bessel function of order \(n\), \(j_n\) is the \(n^{th}\) zero of \(J_0(j)\) and \(D\text{H}_2\text{O}(T)\) is the temperature dependent diffusion constant of water in fused silica. Bell et al [16] gives and expression for the diffusion constant of water in silica based on the measurements in the temperature range from 800°C to 1050°C as

\[
D = 1.0 \times 10^{-6} \exp(-18,300 / RT) \text{ cm}^2/\text{sec for } T \in K \quad (7.3)
\]

The diffusion constant decreases rapidly with temperature because of the exponential dependence of \(1/T\).

The waist region of the fused coupler can be modeled as a rectangular waveguide of dimensions \(ax2a\) and uniform index of cladding formed by air. The coupling strength can be expressed as [17]

\[
\kappa \approx \left[\frac{3\pi\lambda}{32a^2n_z}\right] \times \frac{1}{1 + \left(\frac{1}{V}\right)^2} \quad (7.4)
\]

where \(a\) is the core radius, \(n_z\) is the cladding refractive index, \(\lambda\) is the wavelength and \(V\) is the \(V\)-parameter. As water diffuses into the glass, the index drops, resulting in an increase of the coupling strength. The addition of water into the fiber lowers its refractive index such that a fractional increase in the weight of hydroxyl of \(1 \times 10^{-5}\) lowers the index by \(1 \times 10^{-6}\) [14].

Another field failure mechanism in monolithic fused devices is strain from adhesives causing relative motion between the fused fibers, affecting the structural integrity of the fused region and eventually leading to a device failure. The analysis indicates that such kinds of failures starts from small surface defects caused during the fusion or pre-fusion process and further accelerated by the thermal strains or impact due to rough handling at the outside plant conditions [18]. Factors such as worn-out fiber strippers can cause surface defects [19]. The cracks or small surface defects in the fused region grow slowly, causing a silent disconnection. Incases where only one of the fibers among the fused bundle is having problem, strain will be accumulated on the other fibers, thus leading to no-power condition of the product. Figure 7.2 shows the SEM photograph of a failed monolithic coupler. Another prominent failure mechanism observed is the loss of adhesion between the epoxy and quartz substrate to which the fused fiber is bonded. When the fiber bundle detaches from the quartz substrate, it exerts strain on the fused region, ultimately leading to a no-light
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condition. Even when the typical failure rate is less than 0.1%, it can still be severe, as it can disrupt the service to multiple customers, depending on physical location of the device in the network.

![Figure 7.2: SEM picture of failed couplers with magnification of 35 & 400 respectively](image)

Fused couplers must withstand the strains from impact and thermal variations as well as humidity variations at outside plant environments, to offer zero defect PON systems. But all fused couplers are sensitive to environmental effects to some extent, causing long term splitting ratio drifts and increase in polarization dependent loss. Methods were tried to improve the thermal stability of couplers using “glass solder technique”, where the glass solder provides a thermally well-matched bond between the quartz substrate and fiber [15]. This method helps to improve the stability of the insertion loss with temperature. However, this doesn’t improve the impact resistance. Couplers built with conventional methods and glass solder couplers failed, when bare dropped from a height of 3 ft. The present analysis has been made in specific reference to the fused monolithic 1x4 couplers, made using Corning SMF28 fibers.

7.3 Packaging Design Improvements

Here modifications are suggested for the basic packaging approach described in section 7.1, to improve the performance. Field failures originate from various types of strains, when exposed to outside plant environment. There are mainly two different types of strains that affect the integrity of the fused region. Intrinsic strain sources include strain from twisted fibers, tension in the fused region etc. Extrinsic strains mainly come from adhesives, from substrate or secondary tube. The modelling and analysis of vibrational and thermal strains towards fused region, indicates that change
in the primary packaging technique can effectively isolate various intrinsic and extrinsic strain sources [20].

7.3.1 Thermal Stability

The insertion loss of the coupler should remain stable, when it is subjected to varied thermal conditions. The strain from epoxy can be a problem to the integrity of the fused region, when subjected to continuous thermal / humidity cycling. The exposure to humidity causes water absorption of the adhesive leading to a volume increase, which in turn applies strain on the coupling region. Defects on the surface of the taper grow under the combined effects of humidity and strain and can eventually cause a fiber fracture. Also the epoxy exerts strain due to the thermal expansion thus affecting the thermal stability of the product. The packaging substrate and the optical adhesive to be used should ideally have identical behaviour as that of the fiber glass material. The selection of epoxy shall be made with two parameters: low water absorption and low coefficient of thermal expansion (CTE) to ensure the long-term stability. No adhesive is available which applies zero strain to the fused region; the one having minimum thermal expansion coefficient is $15 \times 10^{-6}$ in/in/°C. However, the CTE can be further matched to that of fiber, by suitable fillers like quartz powder, which improves the thermal stability considerably. Figure 7.3 shows the thermal stability values with different quartz fill ratios. The variation between the maximum and minimum insertion values, when the coupler is subjected to thermal cycling, is taken as the thermal stability in dB. The thermal stability is measured by monitoring the insertion loss online. Figure 7.3 shows the average thermal stability value of 10 products fabricated with the specified quartz fill ratio. The stability is found to be better when the quartz fill ratio is around 1:1. But above this fill-ratio the thermal stability gets degraded, may be due to the poor adhesion.

Couplers fabricated with a quartz fill ratio of 1:1 were subjected to thermal shock, by varying the temperature between –40 and +90 Degree with a ramp rate of 13°C/min. Each coupler was tested for this temperature cycle and is actively monitored throughout the test. The couplers exhibited minimal sensitivity to changes in temperature; the typical change was less than 0.1dB. The typical thermal stability graph of 1x4 splitter is shown in Figure 7.4.
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![Thermal Stability Plot](image1)

**Figure 7.3:** Thermal stability plot with different quartz fill ratios

![Insertion Loss Variation](image2)

**Figure 7.4:** Insertion loss variation with temperature for a 1x4 coupler

### 7.3.2 Epoxy Adhesion

Loss of adhesion between the fiber and epoxy is another reason why couplers get failed in fields [21]. Thermally cured epoxies provide the necessary adhesion to maintain the structural integrity of the couplers. But the physical properties of the epoxies are affected by uncontrolled environmental conditions. Exposed to harsh environment (85°C/85%RH) and in the presence of strains, thermally cured epoxy is found to lose its adhesion with quartz substrate and to hold the fibers in place. It is seen that in some of the couplers, the bond got peeled off from the substrate after exposure to thermal cycling. This effect can be reduced by providing suitable...
roughness to the quartz substrate. Figure 7.5 shows the performance of the coupler, when quartz substrates of different surface roughness are used. There is an obvious improvement in the performance of couplers made with 50 and 80 micron roughness with respect to the products made with zero surface roughness. However, the 150micron thickness does not give much performance improvement. Here 150micron roughness is created with mechanical process, which might have degraded the structural strength of the substrate. A failure is defined as a change in insertion loss by 0.25 dB. The percentage of failure decreased to <5%, when the surface roughness is increased to of 80µm (rms value).

![Figure 7.5: Performance chart with different surface roughness for the quartz substrate](image)

### 7.3.3 Impact Resistance

Fused couplers are exposed to impact at fields, during installation and handling. It is found that a drop of a product from height of 1 ft can make it non-functional, which can happen at any time between the manufacturing process and installation. To minimize the effect of impact towards the fused region, the criticality lies in defining adhesive application points as well as the distance between such points. Traditional epoxy application methods are focussed on holding the fibers to the substrate, but are not applied to absorb the twisting strains. During impact and thermal stress, the twisted portion is still free to move and exert pressure on the fused region, ultimately causing a disconnection. To improve the impact resistance and thus to withstand drop tests, fused couplers shall be affixed to the substrate in such a way that the epoxy absorbs the strains from fiber twists completely. This method of adhesive application restricts the relative motion between the fibers and improves the drop test.
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performance. But the application of adhesive does not cause changes in the insertion loss of the device. The impact resistance is tested by dropping the couplers from 1ft height on a concrete surface. The insertion loss is online monitored during the drop and a change in IL for more than 0.5dB is judged as a fail. Figure 7.6 shows the number of samples failed when 20 couplers are subjected to drop tests, each batch is made with a specific epoxy length. The epoxy length is measured from the unstripped portion of fiber towards the fused region. Redefining the epoxy application points improves impact resistance. However, there is a limit on the maximum length of epoxy, since its affects the thermal stability as well as IL due to epoxy wicking. There exists a region, where both the parameters are acceptable. Thus it is necessary to make a balance between the above two factors, to achieve the impact resistance as well as good optical performance.

The bare drop test performance of new couplers is compared with the standard designs and a five-fold improvement is observed. Sample A is selected from a standard coupler manufacturer and Sample B is the optically soldered product. Sample C contains the newly designed couplers. Each lot contains 20 products and the test result is summarized in Table 7.1. Comparative study of samples indicates that the new design offers good performance and withstands bare drop tests. The products were online monitored during drop and passed products showed no variation in their optical performance, during or after the drop. This improvement in drop test performance is attributed to the new method of coupler fixing to the substrate, where the adhesives are applied in such a way that the residual tension at the fused region is minimal.

![Figure 7.6: Drop test and insertion loss data of fused couplers](image)

Figure 7.6: Drop test and insertion loss data of fused couplers,
with different epoxy lengths

<table>
<thead>
<tr>
<th>Product Type</th>
<th>Sample A</th>
<th>Sample B</th>
<th>Sample C</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of Samples</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Products Passed</td>
<td>4</td>
<td>9</td>
<td>19</td>
</tr>
</tbody>
</table>

Table 7.1: Bare Drop Test summary of different coupler designs

### 7.3.4 Humidity Resistance

![Figure 7.7: Humidity performance of the couplers with different end sealant lengths.](image)

All epoxies are susceptible to attack from humidity. Swollen epoxies exert pressure on fused region. Also it is recently reported that SiO$_2$ structure gets loosened at the fusion region [22], causing water molecules to penetrate. This causes shift in coupling ratio of couplers, when exposed to high humid environments. Couplers with enhanced resistance to environmental conditions were demonstrated by Tallent et al with deuterium gas [23]. Performance improvement in humidity can also be achieved with suitable secondary packaging designs. This is achieved by increasing the silicone end booting of the product. Improvements in long term performance are observed by varying the sealant length, which effectively increases the water creeping length. Figure 7.7 shows the average time in hours, the couplers performed with in the criteria when exposed to humidity conditions. The failure condition is defined as variation from the initial value by 0.3 dB.
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7.4 Reliability Tests

Monolithic 1x4 couplers are packaged as described in section 7.3. To ensure the performance, these couplers were subjected to temperature cycling and humidity aging tests as per Telcordia standards [24]. A failure is defined as a change in the insertion loss over 0.5 dB in the operating bandpass around 1310, 1490 and 1550 nm. The results of temperature cycling and humidity aging tests are summarized in the Table 7.2. The results show that the optical performance is very stable after these accelerated tests. After humidity aging, the average increase in Insertion Loss in all the ports is less than 0.25 dB. These tests were conducted on a batch of 11 numbers and the performance is tested for all the ports over the entire wavelength range. The test values in Table 7.2 confirm the stability of the new packaging scheme.

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Number of Cycles / Days</th>
<th>Average Increase in Insertion Loss</th>
<th>PDL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Cycling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 Cycles</td>
<td>0.03</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>200 Cycles</td>
<td>0.05</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>500 Cycles</td>
<td>0.06</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Damp Heat Testing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 Days</td>
<td>0.08</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>42 Days</td>
<td>0.13</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>83 Days</td>
<td>0.25</td>
<td>0.18</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.2: Changes in optical performance parameters

The high power handling capability of these couplers are tested, by exposing it to a +23dBm EDFA built in house. The test setup is illustrated in Figure 7.8. The DUT is
placed in elevated environmental condition at 85°C and 85%RH to see any degradation. No significant drift in IL is observed for 4000 hours.

### 7.5 Conclusions

Several packaging changes were tried and analyzed to improve the long term performance of monolithic fused couplers. Eventually, a stable packaging technique involving use of quartz substrate, thermally curable epoxy has been developed and successfully tested for their stable performance. The proposed design changes are applicable for all fused devices, including monolithic couplers and wavelength division multiplexers. It is concluded that truly fused 1xN devices could meet the reliability coefficients required for PON applications and SASAs based on these couplers are good choice for future FTTH applications.

### References


