High Reliability Optical Splitters Composed of Silica-Based Planar Lightwave Circuits

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***Abstract*— The environmental and mechanical reliability of a planar lightwave circuit (PLC)-type optical splitter modules is investigated with reference to the Bellcore requirements. The module is composed of Y-branching silica-based waveguides on Si connected to optical fiber with UV-curable adhesives and is packaged in a metal case which is filled with humidity-resistant resin. High optical performance such as low loss, low reflection, and thermal stability are obtained through the use of this fiber connection technique. Ten reliability tests including long-term environmental and mechanical tests were carried out for more than ten PLC splitter modules. Under one of the most severe sets of conditions (75°C and 90% RH), all the 19 samples we tested were stable for more than 5000 hours. Other tests confirmed that the PLC splitters offer long-term stability and that their optical characteristics have sufficient mechanical strength. These results indicate that the PLC splitters can be used for practical applications.**

I. Introduction

A VARIETY of optical devices has been developed using silica-based planar lightwave circuits (PLC) fabricated on a Si substrate. They have the advantages of low loss, compact size, low coupling loss with optical fibers and high reproducibility [1]. Among these devices, optical splitters are essential for the construction of optical networks such as fiber-to-the home systems. The PLC splitter is composed of cascaded Y-branching structures and easily can form more than eight output ports.

When the PLC splitters are used in practice, input and output fibers have to be connected to PLC's in order to utilize the integration capability of PLC devices. 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. To attain low loss splitters requires a precise connection method. Moreover, since a PLC consisting of a Si substrate and silica glass is itself very stable, a fiber-to-PLC connection technique will lead directly to a highly reliable PLC splitter. Therefore, it is necessary to establish a precise connection technique and confirm its long-term stability in order to advance the practical use of PLC's.

Up to now, many kinds of connection technique such as fiber fusion splice [2], laser welding [3], and adhesive connection [4] have been undertaken. From a viewpoint of simplicity and cost, connection with UV-curable adhesives [5], [6] can be considered to be the most advantageous. Here we describe a fiber-to-PLC connection technique which uses UV adhesives and consider the factors which govern the connection reliability. We also show the optical performance of PLC 1×8 splitter modules fabricated by this connection technique. We then present the results of reliability tests for the 1×8 splitters with reference to the Bellcore requirements [7], which set some of the most severe reliability test conditions for optical devices.

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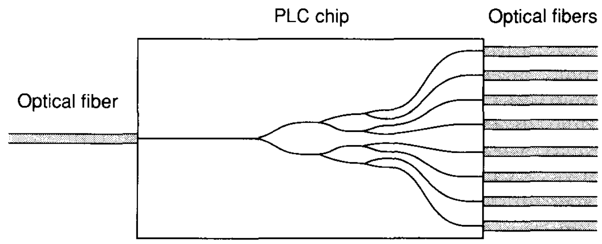

Fig. 1. Schematic structure of a PLC splitter module connected with optical fibers.

II. Reliability Factors

The configuration of a 1×8 PLC splitter chip connected to input and output optical fibers is shown schematically in Fig. 1. One input and 8 output fibers are connected to the chip. Since the core of the PLC is designed to match that of an optical fiber, the connection loss is basically very small (almost zero). So, the module insertion loss is dependent on the precision of the connection technique. The relationship between core deviation and excess loss at 1.55 μm can be calculated from the overlap integration of the mode fields of both the optical fiber and PLC core and is shown in Fig. 2. It is found that a deviation of 0.75 μm leads to a loss increase of 0.1 dB. In order to attain this level of precision, we have developed a fiber-to-PLC connection technique with UV-curable adhesives [5]. This allows us to connect PLC's with optical fibers both simply and with high alignment precision as mentioned below.

Insertion loss, reflectance, polarization dependent loss (PDL) and uniformity are important for optical characteristics of 1×8 splitters connected with optical fibers. To ensure the reliability of 1×8 splitters requires that these characteristics should be maintained for a long time [7]. The PDL and uniformity usually depend on the chip characteristics, and remain unchanged when optical fibers are connected to a chip. However, not only the insertion loss but also the reflectance depends strongly on the connection techniques. The stability of both characteristics is of greatest importance for establishing

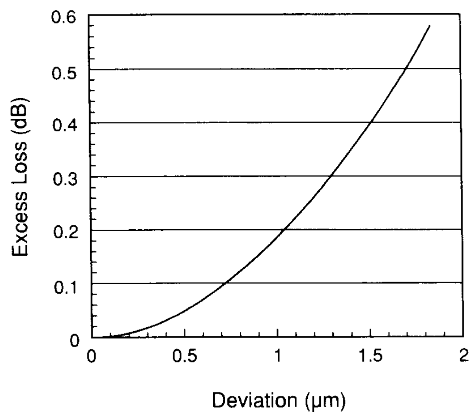

Fig. 2. Relationship between loss increase and displacement at the interface between optical fiber and PLC with a refractive index difference between a core and a cladding of 0.3%.

the reliability of the 1×8 splitters. The factors in the connection technique which have an adverse effect on these two characteristics are considered in the following section.

A. Loss Degradation Factors

Detachment and deviation at the connection interface have the greatest influence on the insertion loss. If detachment occurs at a point on the interface, its area grows and finally the fiber array becomes completely detached from the chip. The detachment results from the diffusion of water molecules and their chemical reaction with UV adhesives. The diffusion and reaction are a thermally-activated process, which strongly depends on the environmental temperature. Moreover, the chemical reactions is determined by the quantity of water molecules. If we select a UV adhesive which has sufficient activation energy with water, the detachment process is governed by the chemical reaction and splitters with a long lifetime can be fabricated. So, it is very important to select a UV adhesive with a high activation energy in terms of its reaction with water molecules.

Moreover, it is possible to suppress the detachment at the interface by reducing the amount of water reaching the connection area. It is useful to package the module to prevent water invasion. For this purpose, we have developed a packaging technique using humidity-resistant polymers. This packaging method will be shown to be effective in ensuring the long-term reliability of the PLC splitters.

A deviation can be induced between optical fibers and PLC by the softening of the UV adhesive at high temperature and the application of stress. This is schematically shown in Fig. 3. The deviation δ is expressed as follows:

$$\delta = (\pi/2)\, d\tau / G \qquad (1)$$

where, d is the thickness of the UV adhesive, τ the shear stress applied to the module and G is the shear stress coefficient of the UV adhesive. Since the stress coefficients of polymers are usually decreased very rapidly near a softening temperature Tg of the polymer, δ depends strongly on temperature. The deviation at the interface causes a loss increase as shown in Fig. 2. In order to prevent this deviation, it is necessary to reduce the thickness d and use UV adhesives with a high Tg. This indicates that the UV adhesives used for splitter-module construction should have high humidity resistance (high activation energy) and a high Tg.

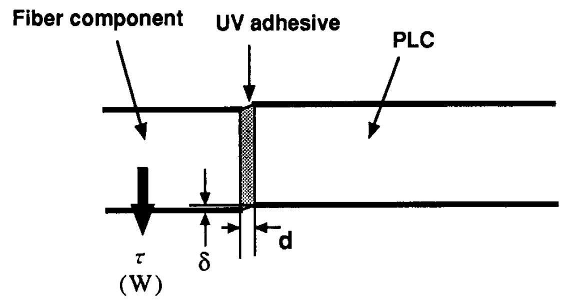

Fig. 3. Side view of a deviation induced by a shear stress at the interface connected with UV adhesive.

TABLE I
AVERAGE REFLECTANCE (DB) FROM FIBER ARRAY SURFACES POLISHED AT 8°

Fibers	Air	UV adhesive
Normal fiber for 1.3 μm	-62	<-75
Dispersion-shifted fiber for 1.55 μm	-57	-65

B. Reflectance Degradation Factors

The reflectance of the PLC splitter modules results from the connection interface between the optical fibers and the PLC chip. Especially, if the detachment occurs at a core region which is polished perpendicularly, the air gap at the detachment results in a strong reduction in the reflectance to more than -20 dB. This is a great problem in terms of the reliability of the splitter. In order to suppress the reflectance at the interface, it is useful to connect the optical fibers and the PLC chip whose both endfaces were polished with an angle . The polished angle is determined from the numerical aperture NA of the waveguides. In order to prevent the backscattered light propagating in the core, the polished angle has to be greater than the angle corresponding to the NA. For a conventional optical fiber with the refractive index difference between the core and cladding of about 0.3%, a polished angle of 8° is sufficient.

The average reflectance values of fiber arrays with a polished angle of 8° are summarized in Table I. The reflectance was measured with a low coherent interferometer method [9]. It is found that a reflectance of less than -50 dB is obtained even in air. So, by using an angle-polished surface, index matching, temperature dependence and interface change can be ignored. The use of this method is expected to greatly improve the reliability of the splitter.

III. Fabrication

Silica-based PLC splitter chips were fabricated on a Si substrate with conventional PLC technology consisting of FHD and RIE techniques [1]. The basic size of the rectangular

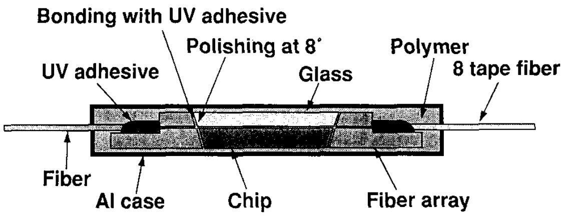

Fig. 4. Side view of a PLC splitter module.

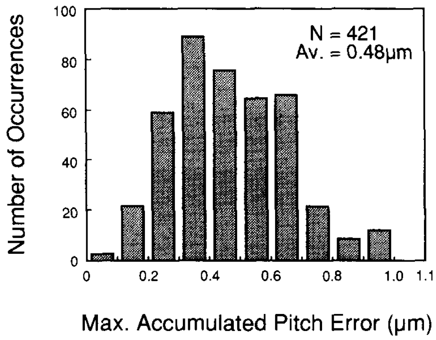

Fig. 5. Distribution of accumulated pitch errors in 8-fiber arrays.

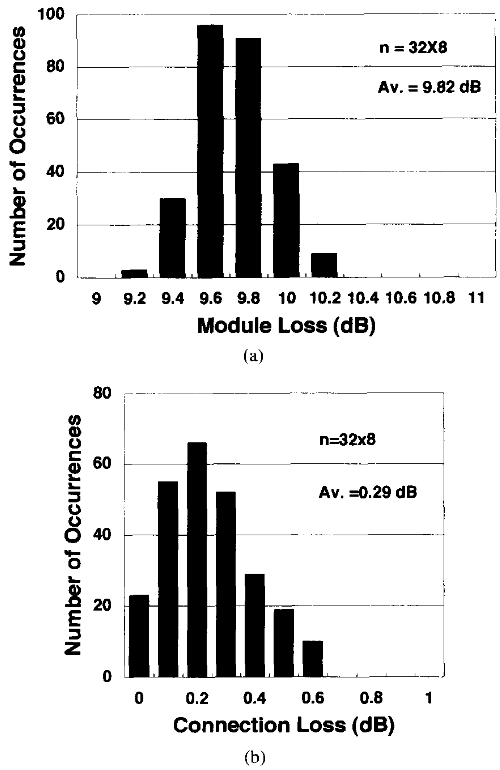

Fig. 6. (a) Distribution of insertion losses in 1 × 8 PLC splitter modules at 1.55 μm, and (b) distribution of connection excess losses in 1 × 8 PLC splitter modules at 1.55 μm.

core was 8 × 8 μm and the refractive index difference between the core and the cladding was about 0.3%. A narrow core about 6 μm wide was inserted before and after the Y branch as a mode filter, reflecting the BPM simulation on cascaded Y-branching structures.

The structure of a PLC splitter module connected to optical fiber with UV curable adhesives [6] is shown in Fig. 4. UV curable epoxy adhesives were newly developed for use with this method [8]. They were found to have a high humidity resistance by an accelerated test using a pressure cooker at 120°C. Eight fibers were arrayed in highly accurate alignment grooves formed 250 μm apart on a glass plate. The fiber array and PLC splitter faces were polished at an angle of 8° as already mentioned. Three components, that is, input and output fiber arrays and a PLC splitter were aligned and then connected together with UV adhesives. Three kinds of splitter module were fabricated in order to compare the reliability. The three modules A, B and C had different sectional areas for the connection of 40, 10, and 4 mm^2, respectively.

The fiber-connected 1 × 8 splitter module was packaged in an Al case, which was filled with humidity-resistant polymer to increase the reliability. The dimensions of the packaged 1 × 8 splitter were 7 × 8 × 80 mm.

IV. Optical Characteristics

The connection loss between the PLC splitter and the optical fibers was mainly determined by the accuracy of the fiber array pitch because the waveguide pitch is precisely formed by the photolithography. The accumulated pitch errors in the 8-fiber array were obtained by measuring each core center for the 8 fibers. The accumulated error is a sum of the difference between a measured value and a pitch of 250 μm. The distribution of the maximum accumulated errors for 421 fiber arrays are shown in Fig. 5. The average value was about 0.5 μm, showing that an 8-fiber array with very precise pitch can be fabricated.

We estimated the optical characteristics of a fiber-connected PLC splitter module which was fabricated using the above 8-fiber arrays. In order to evaluate the connection loss, the chip and module losses were compared for eighteen 1 × 8 splitter chips at 1.3 and 1.55 μm. The average losses for the chip at 1.3 and 1.55 μm were 9.69 and 9.56 dB, respectively. Based on these values, we estimated a waveguide loss of 0.06 dB/cm and a Y branch loss of 0.13 dB/point for both wavelengths. The module loss and connection loss are shown in Fig. 6 (a) and (b), respectively. The loss was measured with fiber splicing and a cutback method. The maximum loss of the fabricated 1 × 8 module was less than 10.5 dB at both 1.3 and 1.55 μm. The average connection loss between the 8-fiber array and the PLC splitter was estimated at about 0.15 dB/point, which is comparable to that already reported [4]. Moreover, typical loss spectra of 8 ports in the fiber-connected 1 × 8 splitter are shown in Fig. 7. The insertion loss range is ranged within 1.0 dB, indicating that the wavelength dependence of the loss is small in the PLC splitters.

The reflectance from the interface between the fiber and the PLC was also measured with a low coherent interferometer method [9]. The reflectance was less than −60 dB at both

TABLE II
SUMMARY OF RELIABILITY TEST RESULTS FOR PLC SPLITTER MODULES. THE TABLE LISTS AVERAGE AND MAXIMUM LOSS CHANGES AFTER THE TESTS

No.	Test	Duration	Sample No.	Av. (dB)	Max. (dB)
1	Damp heat (75℃, 90%RH)	5156 hours	19	0.01	<0.4
2	High temp.(85℃, <40%RH)	5090 hours	11	0.09	<0.3
3	Low temp.(-40℃)	5003 hours	11	0.03	<0.3
4	Temp. cycle (-40~75℃)	503 cycles	11	0.05	<0.3
5	Temp./Humid. cycle (-40~75℃90%RH)	5 cycles	11	0.09	<0.3
6	Heat shock (ΔT=100℃)	20 cycles	11	0.01	<0.2
7	Water immersion (43℃)	168 hours	11	0.01	<0.2
8	Salt spray (35℃, 5%)	〃	11	0.02	<0.3
9	Vibration (10~2000Hz)	12 cycles(x,y,z)	11	0.1	<0.2
10	Airborne Contaminants	30 days	5	0.05	<0.2

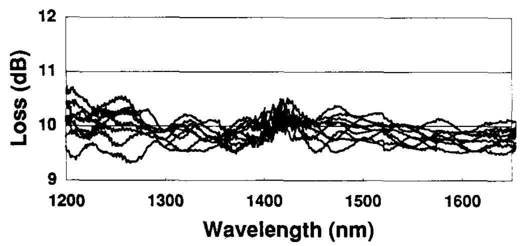

Fig. 7. Typical loss spectra of 8 ports in a 1 × 8 PLC splitter module.

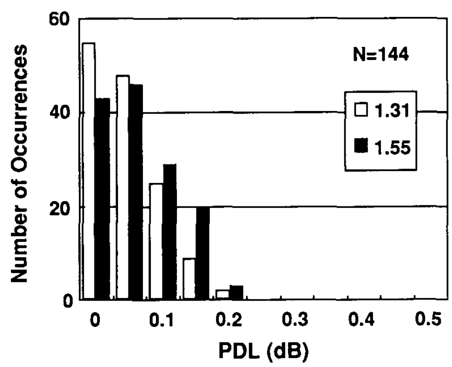

Fig. 8. Distribution of polarization dependent losses (PDL) in 1 × 8 PLC splitter chips at 1.31 and 1.55 μm.

1.3 and 1.55 μm even though the refractive index of the UV adhesive did not match that of silica glass. This is because of the angle-polished faces. These results confirm the precision of the connection techniques.

It is difficult to evaluate the PDL of 1 × 8 splitter modules precisely. So, the PDL of the 1 × 8 splitter chips was measured. The distribution of the PDL are shown in Fig. 8. The average PDL of the 1 × 8 splitters was 0.06 dB at 1.3 μm and 0.07 dB at 1.55 μm and the maximum PDL was less than 0.20 dB. These results illustrate the high level optical performance of PLC devices.

In addition, we investigated loss changes in the 1 × 8 splitter module caused by temperature cycling from −40 to 75°C. The loss change due to temperature cycling has to be checked because the module is composed of parts with different thermal expansion coefficients. Typical loss changes are shown in Fig. 9 including the temperature cycle pattern. The changes of all 8 ports are as small as less than 0.1 dB. The loss change distribution of 8 output ports in eighteen 1 × 8 splitters are shown in Fig. 10. The average changes for the 1 × 8 splitters were 0.19 and 0.14 dB at 1.3 and 1.55 μm, respectively. This result indicates that the module fabrication and packaging techniques suppress the influence of the difference in thermal expansion coefficients and provide the good temperature stability to the PLC 1 × 8 splitters.

V. RELIABILITY

A. Condition and Measurement

Here we describe the reliability of the packaged 1 × 8 splitters which we investigated with reference to the Bellcore requirements. In the requirements, optical performance and reliability test conditions are specified for optical devices. We carried out 10 kinds of reliability test on the 1 × 8 splitters which are listed in Table II and used as least 11 samples for each test. In the tests, we set the failure criteria as an insertion loss of 11.0 dB and a reflectance of −50 dB with reference to the requirements.

In the reliability tests, it is necessary to measure a lot of samples efficiently. The loss and reflectance of a splitter are usually measured by fusion splicing optical fibers, however this is a time-consuming method. So, we developed a method for measuring the insertion loss of the splitters using connectors as shown in Fig. 11. The measurement accuracy is determined by the precision with which the SC connector is connected and is estimated at less than ±0.2 dB. The reproducibility of the SC connector is good enough for the loss criterion of 11.0 dB if the splitter loss is well below 11.0 dB. The reflectance of a splitter with a connector is measured through a input fiber with the low coherent interferometer method as well.

B. Damp Heat Storage Test

Among the reliability tests, damp heat storage at 75°C and 90% RH for 5000 hours is one of the most severe for the PLC splitters because the UV adhesives do not usually have

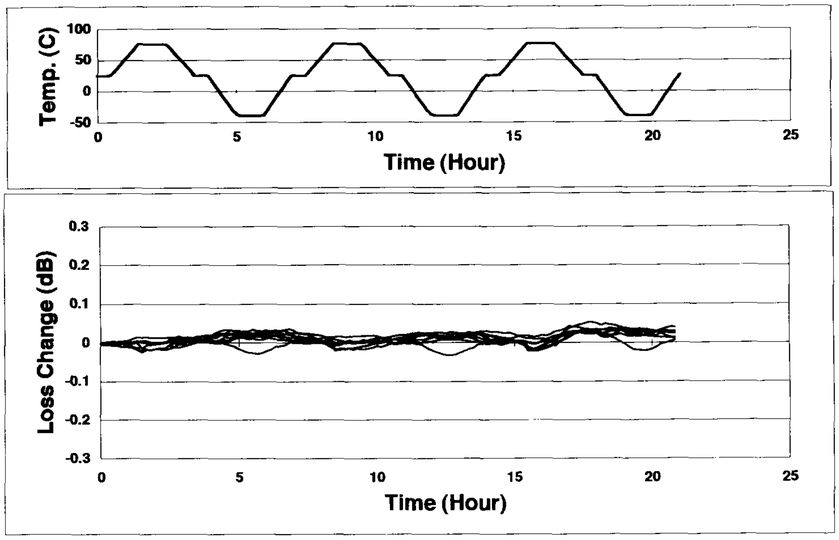

Fig. 9. Typical loss changes of 8 ports in a 1×8 PLC splitter module during temperature cycling from 75 to $-40°C$ at 1.55 μm.

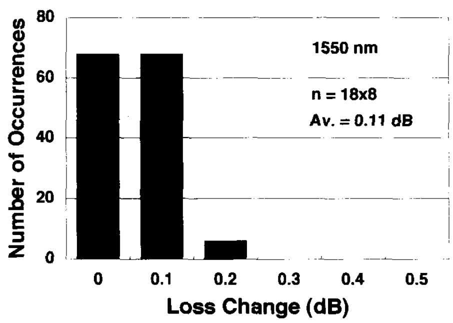

Fig. 10. Distribution of maximum loss changes (every port) in eighteen 1×8 PLC splitter modules during temperature cycling from 75 to $-40°C$ at 1.55 μm.

good humidity resistance. So, we investigated extensively this test. The typical loss changes of the 8 ports in the splitters are shown in Fig. 12. The loss and reflectance were measured offline at the scheduled times. We found that the loss of all 8 ports remained below 11.0 dB for more than 4000 hours. The reflectances were also less than -60 dB because of the angle-polished interface. We then checked whether the sample was in a failure mode during the test. Changes in the maximum loss of ten PLC splitter modules (Sample A) without packaging under the above conditions are shown against elapsed time in Fig. 13. While two samples failed at around 700 and 4000 hours, respectively, the other samples were stable for more than 5000 hours. The results of the damp heat storage test for three kinds of sample with different connection areas are summarized in Fig. 14, which shows the relationship between the number of good samples and time. These results did not satisfy the Bellcore requirements, that is, the criterion of an LTPD of 20%, but suggest that the splitters formed with UV adhesives become more resistant to humidity by increasing the connection area.

We investigated the reliability of the packaged splitter modules stored at 75°C and 90% RH. Changes in the maximum loss for nineteen splitters (Sample A) and fourteen splitters (Sample B) both packaged in Al cases are shown against elapsed time in Fig. 15(a) and (b), respectively. The loss change distribution after more than 5000 hours for the nineteen Sample A splitters are shown in Fig. 16. Moreover, the changes in reflectance (return loss) of fourteen Sample B splitters are shown against time in Fig. 17. The modules were selected by using a screening procedure before the test. The module losses all met the Bellcore criterion of 11.0 dB for more than 5000 hours and the loss changes were within ± 0.3 dB. The reflectance in Sample B remained almost unchanged during the test because of the tilted faces. This result shows that the PLC splitters satisfy the criterion that is an LTPD of 20%. In addition, the long-term stability of even Sample B with the smaller connection area is improved greatly by packaging. From these results, we found that the UV adhesives have sufficient humidity-resistance and that the packaging method is effective in preventing water invasion.

C. High and Low Temperature Storage Tests

Changes in the maximum loss for eleven modules (Sample B) stored at a high temperature of 85°C and less than 40% RH are shown against time in Fig. 18. The module insertion loss was also stable for more than 5000 hours even in Sample B. This result indicates that the UV adhesives we used are stable at high temperature and have a high enough Tg to prevent deviation due to softening.

A low temperature storage test at $-40°C$ was also carried out for 11 packaged modules (Sample B). The changes in the maximum loss of eleven modules are shown against time in Fig. 19. The module insertion loss was also stable for more than 5000 hours. This result indicates that the UV adhesives are stable at a low temperature.

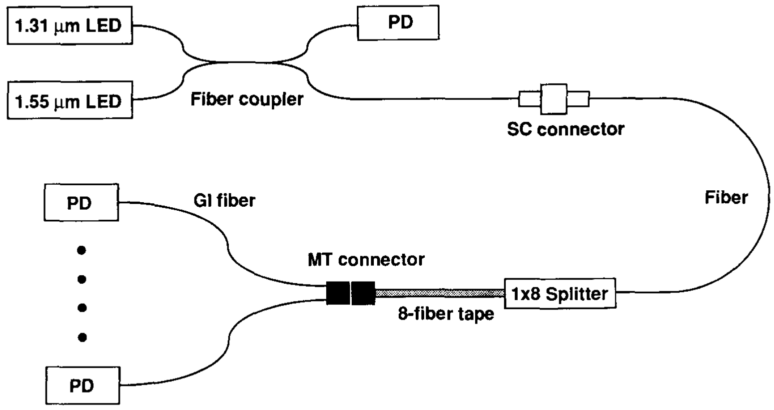

Fig. 11. Loss measurement system of a 1 × 8 PLC splitter module using optical connectors for the reliability tests.

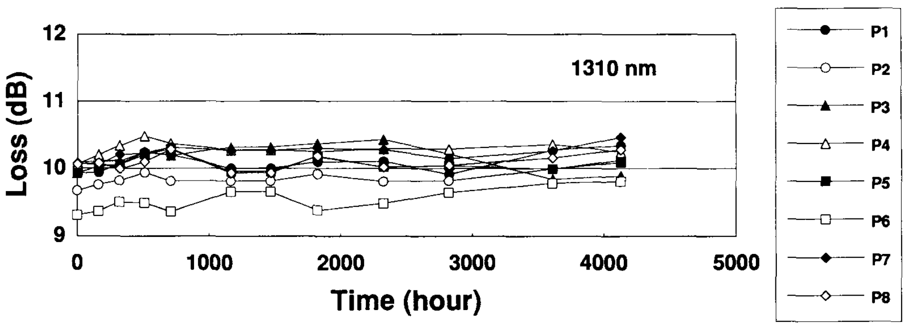

Fig. 12. Typical loss changes of the 8 ports in a 1 × 8 PLC splitter module during a damp heat storage test at 75°C and 90% RH at 1.31 μm.

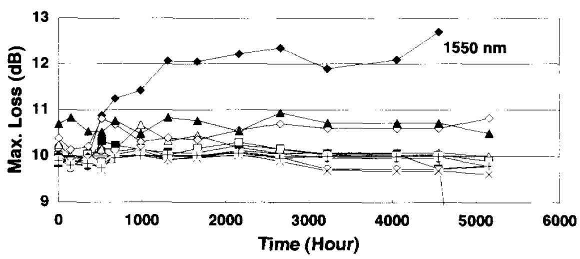

Fig. 13. Changes in the maximum loss of ten PLC splitter modules (Sample A) without packaging at 75°C and 90% RH against elapsed time at 1.55 μm.

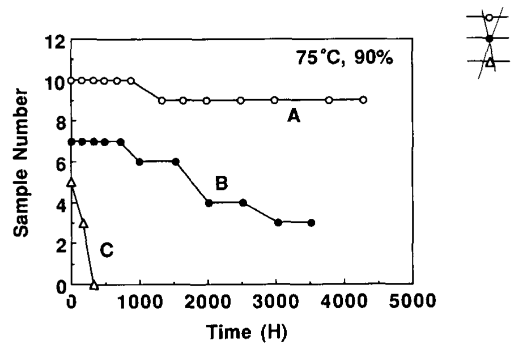

Fig. 14. Relationship between the number of good samples and time in the damp heat storage test (75°C and 90% RH) for three kinds of sample with different connection areas.

D. Temperature Cycle Tests

Two kinds of temperature cycle test were carried out. In one, the temperature was changed from −40 to 75°C, and held for 1 hour. In this test, the stress influence due to the difference in thermal expansion coefficients among the parts of which the splitter module was composed can be investigated. The maximum loss changes for eleven packaged splitters (Sample B) during 503 cycles are plotted in Fig. 20. The maximum loss changes of the eleven samples were almost less than 0.3 dB and every module satisfied the Bellcore optical criteria. This result indicates that the stress is suppressed in the module.

In the other test, humidity of 90% RH was added at 75°C. The loss change distribution after the test for the eleven samples is shown in Fig. 21. The average loss change in the samples after five cycles was as low as 0.06 dB. These two results indicate that the PLC splitter can be used for a long time in an environment with a large temperature variation.

E. Reliability Test Summary

The reliability test results, including those for environmental and mechanical tests based on the Bellcore requirements, are summarized in Table II. The results of Tests 1–5 are

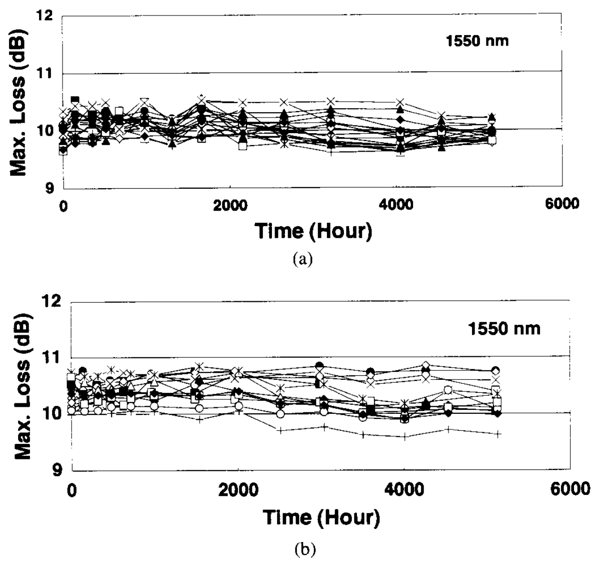

Fig. 15. Changes in maximum loss of PLC splitter modules packaged in an Al case and polymer in the damp heat storage test at 75°C and 90% RH at 1.55 μ. (a) Sample A: 19 samples. (b) Sample B: 14 samples.

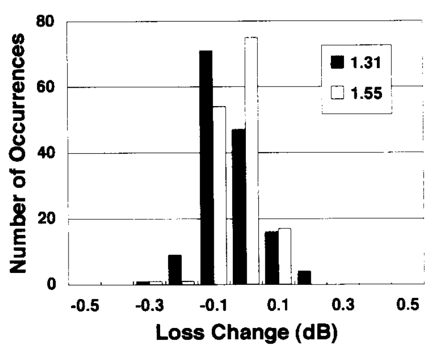

Fig. 16. Loss change distributions of 19 splitters (Sample A) after 5156 hours at 75°C and 90% RH.

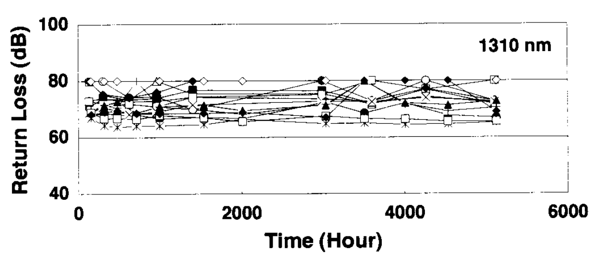

Fig. 17. Changes in reflectance (return loss) of 14 splitters (Sample B) stored at 75°C and 90% RH at 1.31 μm.

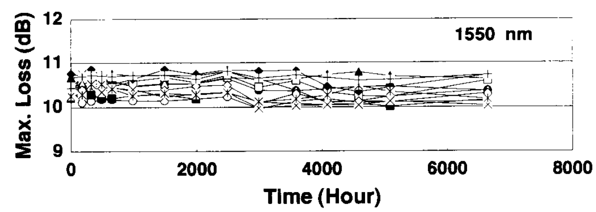

Fig. 18. Changes in the maximum loss for 11 splitters (Sample B) stored at a high temperature of 85°C and less than 40% RH against time at 1.55 μm.

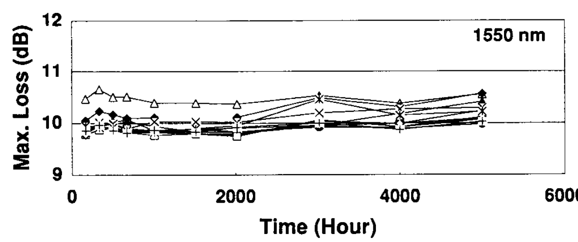

Fig. 19. Changes in the maximum loss for 11 splitters (Sample B) stored at a low temperature of 40°C against time at 1.55 μm.

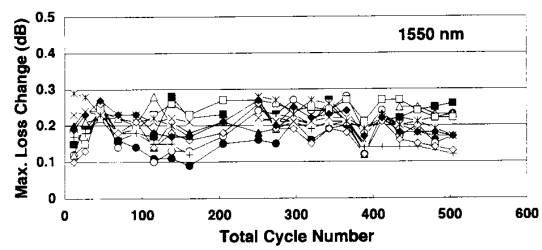

Fig. 20. Maximum loss changes in 11 packaged splitters (Sample B) during 503 cycles at 1.55 μm. The temperature was changed from 75 to −40°C as shown in Fig. 9.

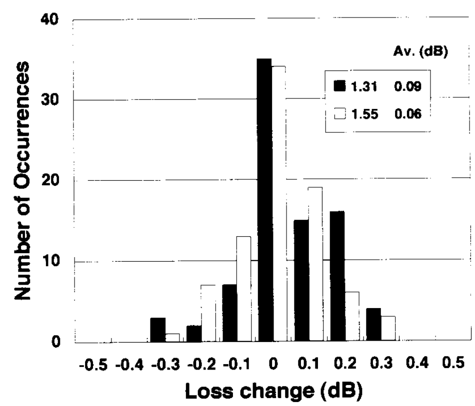

Fig. 21. Distributions of loss changes in 11 samples (Sample B) after five damp-temperature cycles in which humidity of 90% RH was added at 75°C.

described above in detail. In the other Tests (6–10) which are short-term tests, there was no 1 × 8 splitter which did not meet the Bellcore criteria. These results confirm that the splitters have a sufficient mechanical strength as well as long-term stability under severe environmental conditions. This reliability results from the newly-developed adhesives and the packaging method.

VI. Conclusion

We reported the optical characteristics and reliability of silica-based PLC 1 × 8 splitters. Good optical performance including low PDL, low fiber-to-PLC connection loss and high temperature stability were obtained. The results of reliability tests, which were carried out with reference to Bellcore requirements, confirmed both the long-term stability under severe conditions and the mechanical strength of the 1×8 PLC splitters. We believe that these results will accelerate the use of PLC splitters in the construction of optical networks.

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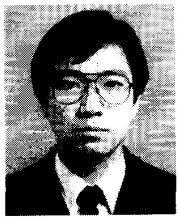

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