Optical Componentry Utilized in Field Trial of Single-Mode Fiber Long-Haul Transmission

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(*Invited Paper*)

***Abstract*—Realization of large-capacity long-haul transmission systems is now quite promising due to rapid development in the field of optical fibers. This paper describes single-mode fiber optical components for use in the above-mentioned system. In particular, LD modules and optical connectors are most important for construction of a practical system. Thus, they are explained in detail along with their development procedures. Important field trial results of these components are also presented.**

I. Introduction

OPTICAL fiber transmission has many potential applications owing to the remarkable characteristics of optical fibers [1]. At present, many research and development programs and field trials are being carried out for the realization of practical optical fiber transmission systems [2]-[8].

Optical fibers, light sources, and photodetectors are fundamental devices to construct an optical fiber transmission system. In addition to these devices, such optical components as light-source modules (light source-to-fiber coupler), photodetector modules, connectors, and splicing are essential to realize a practical optical system. Optical multiplexers, switches, and isolators are also necessary for more advanced optical systems. Furthermore, optical attenuators, directional couplers, etc., are required for the measurement of optical transmission systems. Major multimode fiber optical components have already been developed for the multimode fiber transmission systems (e.g., medium-capacity short-haul transmission systems), although several other components are still in the developmental stage.

Single-mode fiber (SMF) optical components require more efforts for use in the SMF transmission systems (e.g., large-capacity long-haul and submarine transmission trunk systems). This is due to the following reasons:

1) Critical submicron accuracy is required for SMF component fabrication and assembly.

2) For the SMF transmission systems, highly graded SMF components must be realized with low coupling loss, low insertion loss, high reliability, etc.

At the Electrical Communication Laboratories (ECL) of Nippon Telegraph and Telephone Public Corporation (NTT), field trials on the medium-capacity short-haul transmission system (SH system) were carried out in 1978 and 1980 [2], [8]. And subsequently, a plan was initiated for the large-capacity long-haul transmission system (LH system) whose field trial is now underway. The outline of this system has been described in [9] and [10].

LD modules, connectors, attenuators, etc., have been developed for the LH system. This paper puts an emphasis on the SMF components developed for the LH system. Section II reviews the research and development of optical components required for the optical transmission systems. Newly developed components for the SMF system are presented in Section III. The results of the field trial are shown in Section IV.

II. Development Procedure

A. Evaluation of Multimode Fiber Components

In 1977 the SH system was chosen as an initial optical transmission system [11], [12]. The system was based on multimode fiber technology, whose capacity was 6, 32, and 100 Mbits/s, and the repeater spacing was about 10 km. We have been developing several optical components applied to the system [13], [14]. At that time, optical components were classified according to application. They were: 1) components for basic system construction (a basic system construction is defined as a simplified system construction that contains fiber, light source, photodetector, light-source module, connector, splicing, and so on); 2) components for advanced system construction (an advanced system construction is defined as a complicated system construction that contains all the essential components of the basic system construction plus switch, multi/demultiplexer, isolator, and so on); 3) components for measurement that are applicable to any system construction. Table I shows classified components.

Development of the components advanced between 1977 and 1980. During that time, several important achievements were obtained [13]-[24]. The applicability of these components was evaluated by the laboratory test and field trials of the above-mentioned SH system. Attainability evaluation of the components is also shown in Table I. Circles and triangles represent the practical application stage and the fundamental development stage, respectively. The components for the basic system construction and for measurement were determined for use in the practical system. However, the components for the advanced system were revealed to have several problems, i.e., insufficient stability and reliability.

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TABLE I
REQUIRED OPTICAL COMPONENTS FOR OPTICAL SYSTEM CONSTRUCTION

Classification	Required component	Evaluation
Basic system construction	(a) Light source module [14][15]	○
	(b) Detector module[14]	○
	(c) Connector[13][15]	○
	(d) Splicing[15]	○
Advanced system construction	(e) Multiple connector[16]	△
	(f) Switch[20]	△
	(g) Multi/demultiplexer [17][18][19]	△
	(h) Isolator[21]	▲
	(i) Mixer, Star coupler[22]	△
Measurement	(j) Variable attenuator[23]	○
	(k) Fixed attenuator[23]	○
	(l) Directional coupler[24]	○

○ Practical stage
△ Fundamental development stage
▲ Research stage

B. Problems and Progress of Single-Mode Fiber Components

With remarkable advancements in SMF and light-source technologies [25]-[31], the efforts toward realizing a practical LH system began in 1978 [32]-[35]. The aim of the LH system is to attain large-capacity and long-haul transmission with a capacity of 400-800 Mbits/s and a repeater spacing of 20-30 km, utilizing the SMF broad bandwidth and low-loss characteristics in the long wavelength region. Accordingly, it is essential that optical transmission loss be as small as possible. Therefore, only essential components should be applied to the system's construction, and should have low-loss and high-performance characteristics. With these component requirements as guidelines, LD modules [36], connectors [37] and splicings [38] for system construction, attenuators and directional couplers for monitoring were selected in order to construct the LH system.

A study was conducted as to whether existing components for the multimode fiber system would have the adequate performance when applied to the SMF system. It was clarified that all the components, except for the photodetector module, had to be newly developed to satisfy the LH system requirement. Aspects for designing these components are described below.

1) LD Module for SMF System: The requirements for a practical LD module for an SMF system are as follows:

1) high coupling efficiency,
2) structure for easy fabrication,
3) high environmental reliability,
4) negligible LD performance deterioration.

To satisfy these requirements, it is necessary to develop an efficient LD-to-SMF coupling circuit, perfect a technique for precise mounting of optical coupling elements, and contrive a module construction that is not affected by environmental conditions.

There have been various methods proposed for efficient coupling of an LD to an SMF. They all basically function the same. That is, the LD spot radius of about 0.5-1 μm is magnified to match the SMF spot radius of 5 μm. They are: 1) methods using microlenses with about a 20 μm diameter, such as the cylindrical lens method [36], the spherical lens method [39], the combination lens method [40] of a cylindrical lens and a graded index (GRIN) rod lens and 2) methods utilizing fabricated SMF endfaces, such as the tapered hemispherical end SMF method [41], the microhemispherical lens method [42], and the quadrangular pyramid-shaped hemielliptical lens method [43]. Although these methods may attain high coupling efficiency in experiment by means of precise manipulators, these methods are not free from the difficulties in fabricating a practical LD module. This is due to the stringent requirement of the adjustment of less than 0.5 μm.

To develop practical LD modules for an SMF system, we examined three types of LD modules using 1) the cylindrical lens method [36], 2) the tapered hemispherical end SMF method [41], and 3) the hemispherical ended GRIN rod lens method [44]. As described later, the LD modules that were fabricated using the above methods can basically satisfy the target values. However, some problems remain to be solved with respect to producibility, temperature characteristics, and airtightness.

At present, a newly developed coupling circuit method, i.e., the confocal two-lens method [45], has been applied to LD modules. This method has remarkable advantages, in comparison with conventional methods, as will be discussed later.

2) Connector: Many investigations have been carried out concerning optical connectors for multimode fibers [15], [46]-[53]. There are some that have nearly reached the theoretical connector loss limit (0.3 dB) and are feasible for practical use from the viewpoint of cost and reliability.

An FA (field assembly) type connector developed by the authors [15] has a structure as shown in Fig. 1. The optical fiber is positioned exactly in the center of a precisely fabricated ceramic capillary tube. The connector can be assembled anywhere. Actually, by introducing this connector to the SH system's field trial, excellent performance was ascertained.

On the other hand, SMF connectors have the following difficulties:

1) Due to the considerably smaller SMF core-diameter in comparison with the multimode fiber, the excess loss caused by connector alignment errors becomes quite remarkable.

2) Center alignment accuracy of 1 μm or less is necessary to obtain a connecting loss below 1 dB in the fiber positioning. This requires a submicron-order centering technique.

3) With a high-precision center alignment, deterioration of connector performance may occur due to environmental factors such as temperature, frequent cycle connection, etc.

4) When an LD is used as a light source, pulse-waveform distortion may be caused by the reflected wave generated at the connecting point.

5) In comparison with a multimode fiber, the deviation of SMF structure parameters considerably affects connecting loss.

Because of these difficulties, there are fewer development reports on SMF connectors. The following connector techniques have been reported:

1) the use of a super-precision ferrule with accuracy close to the limit [37], [54],

2) alignment of the fiber by a composed lens to reduce positional misalignment sensitivity [55], [56],

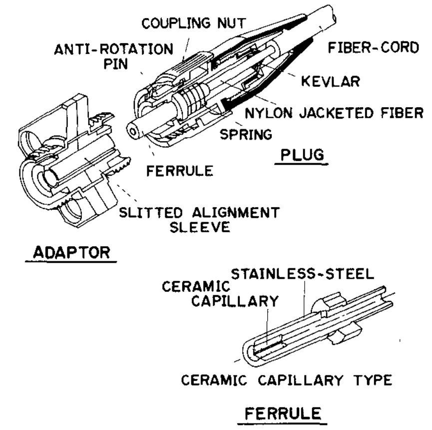


Fig. 1. Schematic drawing of FA-type connector.

3) alignment of the fiber in the center of the ferrule during assembly [57], [58].

The FA connector is fabricated by technique 1). This connector is considered to be the most suitable SMF connector, judging from the success of the multimode fiber connector. So the FA connector was trial manufactured (detailed design is explained in Section III). Among 100 FA connector samples, after mounting the fiber, the eccentricity of the ferrule averaged 0.73 μm and the maximum was 1.5 μm. This fact verifies that a fiber can be connected with an accuracy of 1 μm by butt-joining the ferrules. The connector loss averaged 0.52 dB and the maximum was 1.1 dB. These test results satisfy the system requirements and verify the potential applicability of the FA-type connector. However, further discussion will be required with regard to connector loss stability and a countermeasure against Fresnel reflection.

3) Splicing: The application of the fusion splicing method using an electric discharge was verified for multimode fiber splicing [59]. Also, various automatic machines [60] which align the fiber outer surfaces have been developed for the SH system's installation and splicing. However, in SMF splicing, the eccentricity of the fiber core greatly affects splicing loss. If the conventional fusion splicing machine for multimode fibers is used for SMF's of different lots, then excess loss due to core misalignment is inevitable. Therefore, a splicing machine is required that can adjust the cores center-to-center.

The fusion splicing machine based on the fiber position adjusting method [61], [62] and the elastic deformation method [63] were developed. In connection with this, some important information was obtained.

4) Attenuators: Attenuators are classified into variable attenuators for measuring the error rate, and fixed attenuators for adjusting the optical power level in repeater sections. These attenuators were constructed according to the requirements for multimode fiber transmission systems [14], [23].

Attenuators for SMF transmission systems have basically the same function as those for multimode fiber systems. However, there exist several problems in attenuators for SMF systems. They are: the reflected waves from attenuator elements, the accuracy of controlling the desired attenuation and its resetting accuracy, and the temperature characteristics.

5) Directional Couplers for Fault Location: The optical time domain reflectometry technique [24] is a promising method for locating fiber breaks. The directional coupler used in this technique couples the LD output pulse signals with measured fibers (forward coupling). It also couples the backscattered light of the fibers with the detector (backward coupling). Backscatter light is extremely weak; therefore, direct coupling of the detector and Fresnel reflection lights from various connection points must be reduced as much as possible. It has been pointed out that the directional coupler, using an anisotropic crystal, i.e., calcite, can completely remove the obstructive Fresnel reflection by utilizing the polarization of the LD output power. The directional coupler using calcite has satisfied the system requirements for multimode fiber transmission systems.

There are several difficulties in applying the above-mentioned method to SMF's. 1) Backscattered power in SMF's becomes extremely weak compared with that in multimode fibers. 2) While the searching distance of the breakpoint is about 10 km in multimode fiber systems, it must be extended over about 20 km in SMF systems.

To overcome the above difficultes, not only reduced backward coupling from the Fresnel reflection, but high forward coupling must also be realized for SMF systems. By adopting the efficient coupling circuit used for the LD modules (described later) and a specialized LD [28] which can oscillate at a high-output level, SMF fault location equipment has been realized. This equipment can locate a breakpoint positioned at a distance of up to about 20 km [64].

III. Newly Developed Components

A. Developmental Indices

Main parameters of an LH system for a field trial were clarified [65] in the earlier half of 1980. These parameters are shown in Table II. On the basis of these parameters, the allotted loss to the LD module and connector were investigated. A level of 30 dB was calculated as the difference between the average optical output power and the average optical received power. Calculated fiber transmission loss was 17 dB over a distance of 20 km including splicing loss (3 dB/10 points; 0.3 dB/point). System margin is assumed to be 4 dB. Therefore, 9 dB can be allotted to LD module loss and connector loss, 7 dB to the LD module, and 1 dB per connector (assuming two connectors are installed per repeater spacing of 20 km). Loss variation from temperature changes are included in these figures.

B. LD Modules for SMF System

1) Development of First-Stage Module: Three types of LD modules using 1) a cylindrical lens, 2) a tapered hemispherical end SMF, and 3) a hemispherical end GRIN rod lens have been realized in the first stage of development, as mentioned before. Schematic diagrams of the three types are shown in Fig. 2. These are not laboratory-made modules, but first-stage modules fabricated by a manufacturer to test the practicability of LD modules. Coupling efficiency of the fabricated LD modules are shown in Fig. 3. It is apparent that most of the modules have adequate coupling efficiency according to the −7 dB requirement. The coupling efficiency depends not only on the coupling methods but also on the LD characteristics, e.g., the far-field patterns. Therefore, it is difficult to say

TABLE II
LH SYSTEM'S MAIN PARAMETERS FOR FIELD TRIAL

System capacity	400 Mb/s
Fiber	Step-index single-mode fiber, Loss ≤ 0.7 dB/km at 1.3 μm
Repeater spacing	≤ 20 km
Maximum transmission length	2500 km
Bit error rate	$\leq 10^{-9}$/2500 km $\leq 10^{-11}$/repeater
Light source	InGaAsP-LD
Average output optical power	1 dBm for scrambled RZ
Detector	Ge-APD
Average received optical power at $P_e = 10^{-11}$	≤ -29 dBm

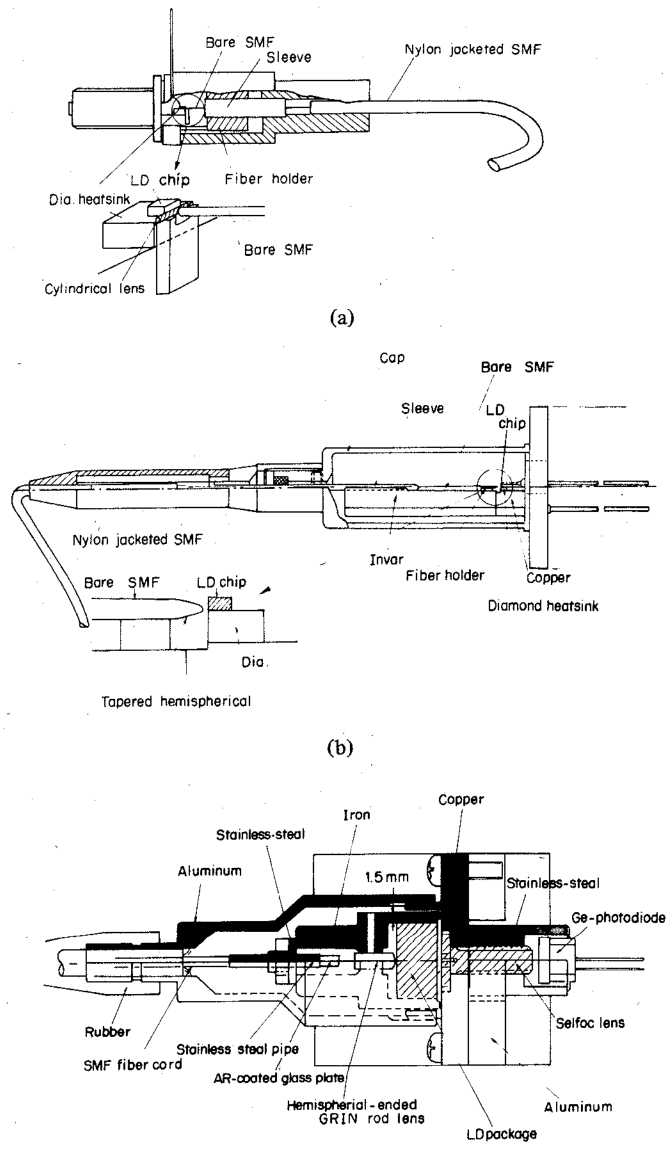


Fig. 2. Block diagrams of three types of first-stage LD modules. (a) Cylindrical lens method. (b) Tapered hemispherical end SMF method. (c) Hemispherical ended GRIN rod lens method.

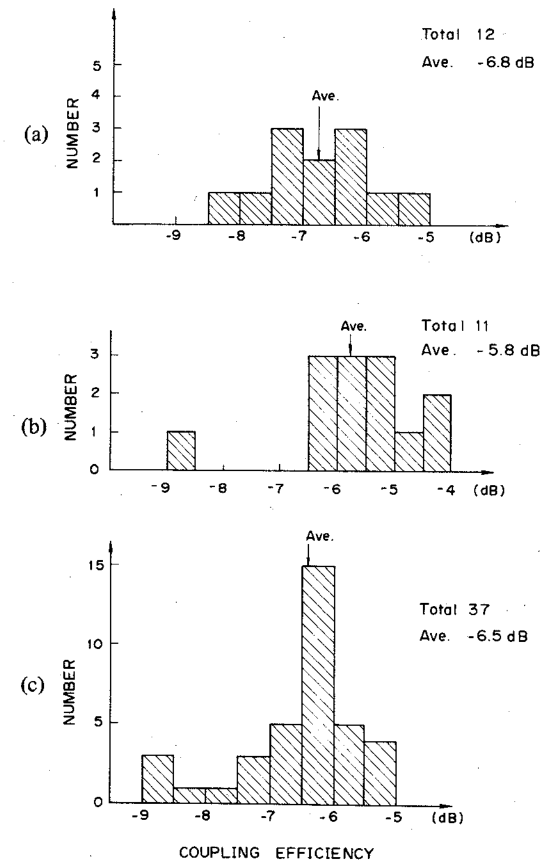


Fig. 3. Coupling efficiency of first-stage LD modules.

which method is best for an LD to SMF coupling; however, generally speaking the (c) type method is inferior to the others because the optical power spilt over the coupling lens periphery is largest due to the low numerical aperture (NA) lens used.

Coupling efficiency variations caused by ambient temperature for the three types of modules are shown in Fig. 4. The temperature characteristics of the LD module is the main problem for the SMF system. This problem is negligible in the multimode fiber LD modules. Some of the LD modules for the SMF system have a large coupling variation of more than 3 dB. The above problem must be solved to realize practical LD modules. The evaluation of the three types of modules are listed in Table III.

The coupling efficiency is theoretically expected to be high for the (a) and (b) types, but deterioration in both coupling efficiency and yield rate are caused by the following reasons according to type.

(a) Type: Optimum distance between an LD and a lens is in the range of 1-4 μm. Since coupling efficiency decreases drastically as distance increases, the both endfaces of the LD chip and the diamond heat sink must be aligned within an accuracy of a few microns in order to optimally position the cylindrical lens. It is difficult to bond the LD chip within this accuracy with the present level of LD chip bonding technology. This is why (a) type LD modules have lower efficiency than expected.

(b) Type: The tapered hemispherical end SMF must be positioned with a precision of less than 0.2 μm perpendicular

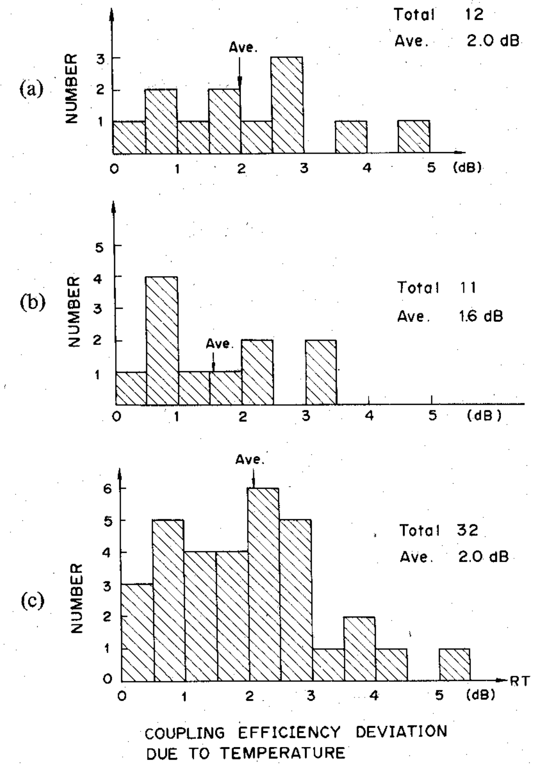


Fig. 4. Temperature characteristics of first-stage LD module.

TABLE III
FIRST-STAGE LD MODULE EVALUATION

Coupling Circuits	Cylindrical Lens Method (a)	Tapered Hemispherical End SM Fiber Method (b)	Hemispherical GRIN Rod Lens Method (c)
Coupling Efficiency	high	high	medium
Producibility	bad	bad	medium
Airtightness	questionable	questionable	good
Stability with respect to Temperature variation	insufficient	insufficient	insufficient

to the LD optical axis, which is the same as methods using the microlens fabricated on the SMF endface. It is difficult, using these methods, to suppress the SMF lateral misalignment during the module assembling process. Therefore, these methods are inferior to the others unless a technique is perfected for positioning the SMF within the accuracy requirement.

An LD chip must be mounted in the hermetically sealed package to secure an LD reliability. Most methods which attain high coupling of an LD with an SMF, use so-called microlenses, as mentioned before, including (a) and (b). It is difficult to seal the LD chip by these methods using the conventional LD package. This is because the SMF must be accurately positioned just near the LD chip. Therefore, a fiber and lens soldering technique must be perfected. We applied the soldering technique to fixing the microlenses or SMF's. However, the accuracy of positioning the optical elements was so poor that epoxy adhesive was used instead for the (a) and (b) type LD modules.

The (c) type method can be applied using the conventional LD package. Although the coupling efficiency is not that good, the module is relatively easy to assemble.

Temperature dependence of coupling efficiency is a common problem among present LD modules. Temperature affects coupling efficiency in the following three ways:

1) coupling circuit offset due to thermal expansion,
2) instability of the LD transverse mode,
3) monitoring power variation.

Coupling circuit offset is due to the thermal expansion difference among the LD, lens, and fiber holders. The lateral offset between the LD and the adjacent lens must be reduced as much as possible because it causes a large offset magnified by the coupling circuit at the SMF endface. It is important to design the module construction so that it can suppress the heat expansion effect.

The required characteristics of LD's suitable for the SMF system are listed in Table IV. Various types of LD's, i.e., BH [29], PCW [31], SAS [27], and CS [30], have been developed. These LD's can basically oscillate at the fundamental transverse mode. Temperature effects are now being studied in detail with respect to the far-field pattern variation.

Optical power levels of the present LD module are checked by a Ge photodetector, which monitors the rear LD output power. This is because half the rear LD output power is reflected by the heat sink, so it is not certain whether the ratio of the front output to rear output is constant or not.

2) Newly Developed LD Module for SMF: A combination lens circuit has been developed using two lenses of different focal lengths positioned in a confocal configuration to solve

TABLE IV
REQUIRED CHARACTERISTICS OF LD FOR SMF SYSTEM

1	Fundamental transverse oscillation
2	Good linearity (Free from kink)
3	Good symmetry and small divergent angle of far field pattern
4	No temperature variation with respect to above items
5	High reliability

the difficulties of the first-stage LD modules. The main advantages of this circuit are summarized as follows:

1) Relatively large lenses available on the market can be used because the optimal image magnification is obtained by selecting the focal length ratio of the two lenses.

2) High coupling efficiency is attainable using LD's in a long wavelength region.

3) Large alignment errors in the assembling process are tolerable for both lenses because of the large lenses used.

4) A glass window can be inserted between two lenses, which enables the mounting of an LD chip together with the first lens in a hermetically sealed package.

5) The first-lens offset, which markedly deteriorates the coupling efficiency, can be reduced by mounting the first lens in a package.

To verify these advantages, LD modules have been fabricated using this method. The first lens is a 0.8 mm diameter spherical lense with a high refractive index. YAG, sapphire, or glass are used. The second lens is a 0.2-0.25 pitch 1.8 mm diameter GRIN rod lens.

A block diagram of the LD module is shown in Fig. 5. The cylindrical mount was adopted for the housing to suppress lateral misalignment caused by temperature fluctuations. The holder of the first lens is attached to the copper stem of the package with adhesive. It is designed so that the holders of the second lens and SMF would not contact the first lens holder directly. A photograph of an LD module for an SMF (8-30 mm) is shown in Fig. 6.

A histogram of coupling efficiency for the test trial fabricated module and also the experimental coupling efficiency using a butt-joint method for comparison is shown in Fig. 7. The average coupling efficiency is -5.5 dB. This is an improvement of 5.7 dB, which is better than that of the first stage coupling circuits. Therefore, realization of the LD module is possible and there is a negligible coupling loss increase due to axial misalignments after assembly.

Output stability from SMF was measured in the temperature range of 5-50°C under an APC (the rear output is kept constant) condition. The maximum fiber output variation caused by ambient temperature is shown in Fig. 8. The average output variation was 1.1 dB in the temperature range of 5-50°C.

The present module is modulated by 400 Mbit/s RZ signals. Frequency bandwidth is about 900 MHz at 3 dB down, and modulation can be performed at a considerably high speed. In connection with this, it has been confirmed that 1.6 Gbit/s NRZ optical signals can be transmitted [66] through a 20 km SMF below the error rate of 10^{-11} using the present LD module.

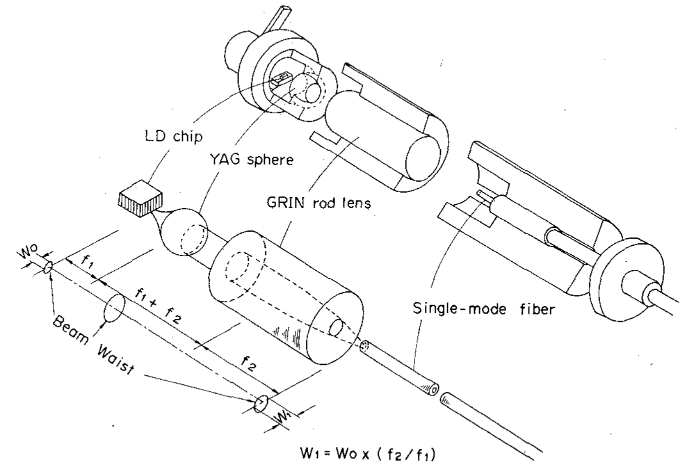


Fig. 5. Block diagram of newly developed LD module.

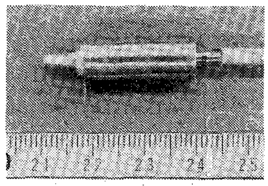


Fig. 6. A photograph of newly developed LD module.

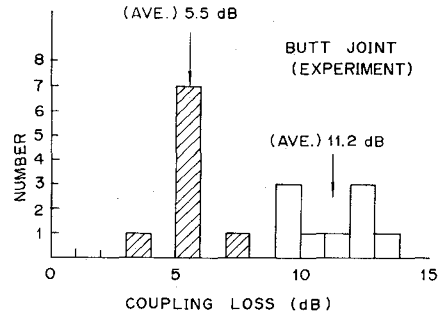


Fig. 7. Coupling loss of newly developed LD module.

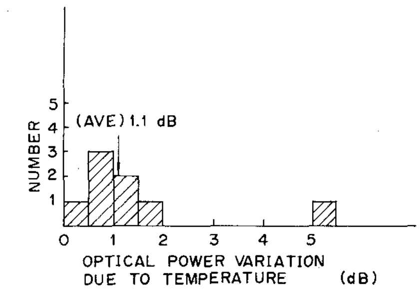


Fig. 8. Temperature characteristics of newly developed LD module.

As to the fault locator equipment, it is necessary to couple LD output power with an SMF through a directional coupler element. It is apparent that the present coupling circuit is suitable for the coupler of the fault locator, since the separation between the two lenses is large enough to insert the directional coupler element.

Precise positioning of elements is necessary for LD module fabrication. It is a general practice for the first-stage modules that lenses and other elements assembled by adhesives and adjustments are made by a precision manipulator. The confocal two-lens circuit requires a lower degree of accuracy, i.e., about a 50 μm offset is tolerable in the process of fabrication because the first lens offset can be compensated for by the second lens. At present, a technique is being studied to fix the first lens by soldering, however, adhesives were used in the trial fabrication. This soldering technique appears to have great potential, and favorable results are expected.

Reflection from coupling elements can cause deterioration of LD module performance. A multilayer dielectric film is applied to each lens as an antireflection coating to suppress this reflection. Optical feedback is strongest when the reflection occurs at the input endface of a fiber. A 0.5-1 mm thick glass plate is attached to the SMF endface with an adhesive to suppress this reflection. Superimposed noises are occasionally seen on the eye pattern due to the reflection of a pigtail output endface. These noises, however, have caused no significant problems that affect SMF optical transmission performance.

It is confirmed that the LD modules developed for the SMF system basically have favorable characteristics that meet the target values. Although temperature dependence of coupling efficiency is somewhat large at present, there is a prospective fabrication technique to overcome this problem by contriving a coupling circuit and a module construction.

C. Connector

In designing the FA-type connector, consideration is given to the factors listed in Table V. Design is based on the degree of allowance given to lateral and angular misalignments. The loss due to misalignment, except for the Fresnel reflection loss of 0.3 dB, is estimated to be 0.4 dB and the sum of both losses (0.7 dB) is determined as the target value. (The worst value of system requirement is 1 dB as shown in Section III-A.)

The degree of tolerance for lateral and angular misalignments is as follows. In designing the FA-type connector, greater allowance is given to lateral misalignment since angular misalignment can be suppressed. This is because angular misalignment can be held down to 0.6 deg or less according to the results of trial manufacture of multimode fibers [15]. The tolerance for lateral misalignment, with a 0.6 deg angular misalignment, is 1.4 μm as shown in Fig. 9. How to allocate this misalignment is an important consideration.

It is important to estimate the actual lateral misalignment when two plugs are connected to each other. This misalignment is calculated by the statistical consideration [67] to be only $\frac{1}{2}$ of the average value of plug misalignments. The same applies to angular misalignment. In view of these facts, the manufacturing dimensional tolerance for each plug is shown below.

Tolerance for outside diameter of ferrule:	± 0.5 μm
Concentricity of cylinder surface and capillary hole:	< 0.5 μm
Tolerance for capillary hole:	External diameter of fiber plus 1 μm
Parallelism of cylinder axis and capillary hole:	0.15 deg.

It is necessary to set the form tolerance (roundness, cylindricity, surface roughness, etc.) and the diameter dimensions for outside diameter of the ferrule. These are all set at 0.5 μm or less. The eccentricity of the plug having a fiber mounting in the ferrule is the sum of the hole/cylinder surface concentricity and the clearance between the fiber and the hole. The design target was set so that the lateral misalignment of one end of the plug endface can be maintained at an average 0.7 μm. The deviation of the plug's outside diameter is absorbed by the slitted resilient sleeve inside the adaptor.

TABLE V
DESIGN CONCEPT OF FA-TYPE CONNECTOR

	Items	Approach
Plug	Lateral misalignment	Cylinder surface/capillary-hole concentricity, Clearance between fiber and hole, Outside diameter tolerance (including dimentional and form accuracy)
	Angular misalignment	Parallelism of cylinder axis and capillary hole
	End separation	Spring-loaded pressure on ferrule
	Fiber end	High precision polishing
Adaptor	Alignment of plug	Form accuracy of resilient guide sleeve, Plug holding force
Fiber	Core/cladding eccentricity, core dia., refractive index difference	Further improvement in fiber manufacturing accuracy
	Fresnel reflection	Connector plug with anti-reflection

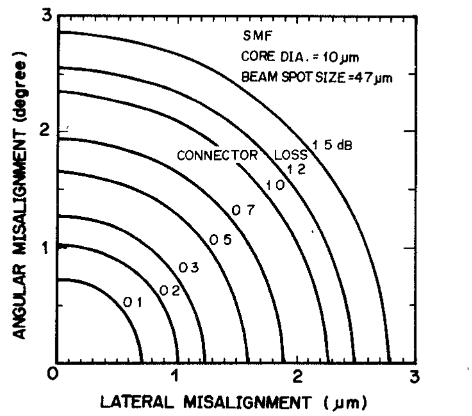


Fig. 9. Design curve for SMF connector.

Angular misalignment is affected by the parallelism of the hole and by its perpendicularity after the endface of the plug is polished. Angular misalignment requirement is set at an average value of 0.3 deg after the plug unit is assembled (called an angle of emitted beam). An increase in loss, depending on the core diameter and refractive index difference, is very small at 0.04 dB even when the deviation in the spot size is about 10 percent [36].

An external view of the connector is shown in Fig. 10. The fitting dimensions are the same as those of the multimode fiber connector. Therefore, the SMF connector and the multimode fiber connector are compatible.

SMF connectors require that the precisional ferrules must be exactly aligned and stably held by the adaptor. With respect to this, the following considerations were made:

1) most suitable value for the compression force of the ferrule and the holding force of the slitted guide sleeve,

2) precise dimensions of parts,

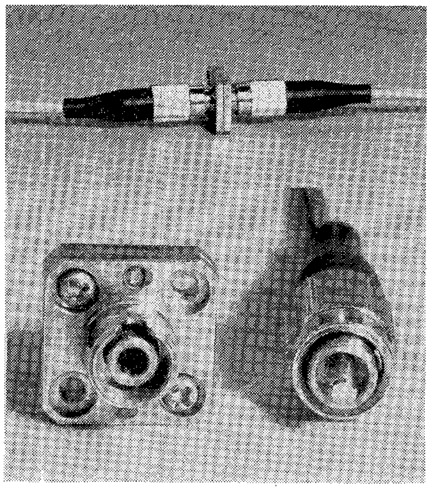


Fig. 10. Photograph of FA-type SMF connector.

3) selection of material with minimum abrasiveness and dust collection.

Based on these considerations, the spring's compression force is 1.2 kg and the adaptor's holding force is 500 g when both ends are inserted.

1) Mechanical Characteristics: About 20 000 units of FA-type ferrules have been manufactured and are being used in connectors for various kinds of optical fiber transmission systems. About 90 percent numbers of these ferrules satisfy the accuracy values shown in Table VI.

From manufactured lots, ferrules which fit the connector specifications for the SMF were selected, and the eccentricity of the plug and the angle of the emitted beam were measured. The results were quite acceptable. For example, the average value of eccentricity was 0.81 μm; the maximum value was 1.4 μm. As to the angle of the emitted beam, an average value of 0.25 deg was obtained. However, in some lots the eccentricity was nearly double the eccentricity of the hole. This value included the eccentricity caused by the clearance between the hole and fiber, and also the concentricity of the core/fiber's external diameter. However, since a high-precision fiber with a concentricity of 0.3 μm or less (0.5 μm maximum) was used, it can be considered that the eccentricity was caused by the clearance between the hole and the fiber.

Next, the assembly process for FA-type connectors is described. The process is simply identical to that of the multimode fiber connector. The endface of the fiber is polished with a buffing machine [68]. Some achievements are: attaining a 1 or 2 μm concavity as shown in Fig. 11; the protection of the endface when mating; and the following characteristic improvements. That is, concave polishing of the fiber decreases multireflection and also contributes to decreasing loss fluctuation by mating and remating, decreasing wavelength dependence connection loss, and stabilizing temperature characteristics.

2) Optical Characteristics: Connection loss of approximately 650 FA-type connectors manufactured for a field trial is shown in Fig. 12. Average connector loss is 0.65 dB, the maximum being 1.0 dB. This shows a low-loss characteristic that satisfies the requirements of the system design. Calculation was performed by taking the average of five mating and remating operations. Furthermore, a plan has been devised to

TABLE VI
MECHANICAL ACCURACY OF FERRULE

Items	Accuracy
Concentricity (cylinder surface and capillary hole)	Less than 1 μm
Outside diameter	2.499 mm ±0.5 μm
Capillary hole diameter	$\phi d\ ^{+1}_{-0}$ μm
External roundness	Less than 0.3 μm
External cylindriform	Less than 0.5 μm
Surface roughness (Rz)	Less than 0.5 μm
Parallelism (cylindrical axis and capillary hole)	Less than 0.1°

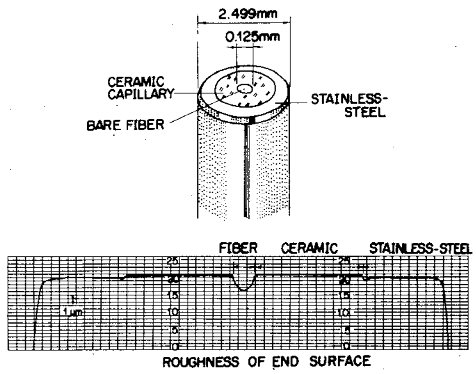


Fig. 11. Polished plug-end surface.

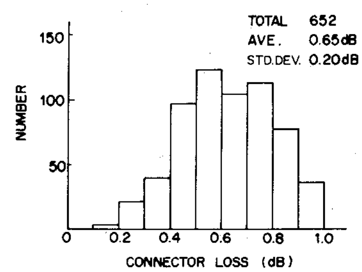


Fig. 12. Measured connector loss of FA-type SMF connectors.

arrange the eccentrical direction of the fiber in the same direction in each plug by adjusting the antirotation pin on the periphery of the plug. This would further reduce connector loss.

Connection loss of connectors installed in the interequipment optical fiber cable at the test site is shown in Fig. 13. A connector loss of as small as 0.55 dB has been obtained. The main feature of this FA-type connector is that it can be assembled in the field as easily as in the factory.

With the further improvement in the trial manufacture, connector loss of 0.50 dB (the average of about 80 units) has been achieved.

In the present SMF transmission system, there has been little deterioration due to the Fresnel reflection of the connector. It is worthwhile, however, to establish the countermeasure against the reflection considering future advanced systems, e.g., gigabit or analog transmission systems. Improvements are being made

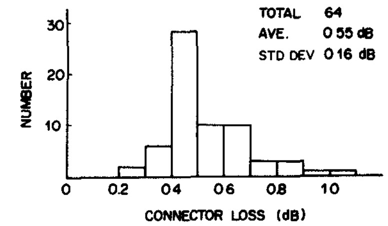


Fig. 13. Measured connector loss of FA-type SMF connectors assembled in test site.

to counter the reflection in the connector by polishing the plug endface obliquely. It has been verified that an improvement of more than 20 dB can be realized by the above method without any additional problems.

3) Reliability Evaluation: The results of reliability evaluation are shown in Table VII. Heat cycle and durability results are shown in Fig. 14. From this figure, it can be seen that stable performance such as the loss change (in the range of -25 to +80°C) is 0.2 dB or less, and 0.2 dB or less is obtained in the 500 cycle mating repetition. These values are about twice as large as those of the multimode fiber. However, they are satisfactory when applied to the present system, and a minimum of 15 kg is adequate for tensile loading. The remaining connector loss factors are all very stable.

D. Attenuators

1) Variable Attenuator: Variable attenuators are mainly used for measuring the *S/N* versus error-rate characteristics of optical repeaters. Besides this, application to optical components and equipment evaluation are being considered, as well as application to optical power-meter calibration.

High precision and a wide variable range of attenuation are required. Accordingly, the wide range of attenuation is secured by combining the variable attenuation plate (in 10 dB steps) and the continuously variable attenuation plate as a pair, by using a rotating mechanism [23]. Moreover, it has been decided to arrange the attenuation plate obliquely against the optical axis, so that the reflection light from the attenuation plate will not return to the input fiber. The design target has been decided and fabrication has been completed. Data are shown in Table VIII. The concrete arrangement is shown in Fig. 15.

Both the continuously variable attenuation plate and the step variable attenuation plate have metal chromium thin films on the optical glass plate. In the continuous attenuation plate especially, the metal film thickness is set so that the degree of attenuation (indicated in dB) will increase in proportion to the rotation angle. The connectors, as mentioned before, are used for the input and output terminals. The inclination angle θ of the attenuation plate has been set at 7°-10° from the results of the basic experiment. Eight variable attenuators were manufactured.

Variable attenuator performance characteristics obtained the target values in most cases, however temperature dependency was somewhat below the target value.

2) Fixed Attenuator: The main purpose of a fixed attenuator is to control optical loss between two repeaters by placing it in front of the optical repeater (directly in front of APD module). A small-sized fixed attenuator with the connector

TABLE VII
MEASURED RESULTS OF CONNECTOR ENVIRONMENTAL TEST

Items	Test Conditions	Change in Connector Loss
Heat cycle	-25°C ∿ +80°C, 10 cycles	< 0.2 dB
Temperature	-20°C, 100H	< 0.03 dB
	+80°C, 100H	< 0.03 dB
Vibration	10 ∿ 55 Hz, Dual amplitude 1.5 mm, 2H for each X, Y directions	< 0.02 dB
Durability	500 mated and unmated cycles	< 0.2 dB
Tensile loading	Breaking point of bare fiber	< 0.1 dB for 16 kg

Total sample number : 100 plugs

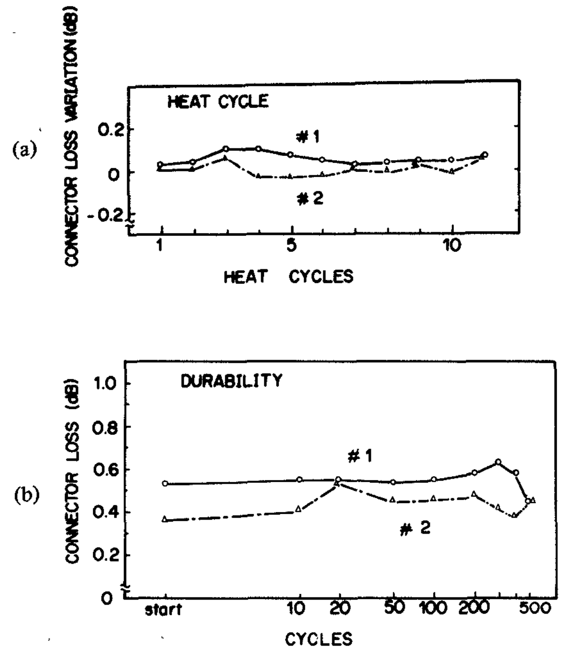


Fig. 14. Results of connector environmental test, (a) heat cycle test, (b) durability.

function is desirable because the connecting and disconnecting operation is performed inside the optical repeater equipment which has a marginally small space. It also requires several attenuation levels. Considering these conditions, the design target values have been set as shown in Table VIII.

As for the structure, a short SMF is built into the connector plug [23], by having one end of the fiber retreated from the plug-end surface according to the desired amount of attenuation. Attenuation is attained by gap-loss occuring at the time when the optical fiber connector is mated.

The relationship between the loss and the size of the fiber gap is shown in Fig. 16. The calculated value and the experimental value coincide. For example, to obtain an attenuation of 10 dB, the gap is 0.35 mm.

The concrete structure of this attenuator is shown in Fig. 17. The gap is made by a spacer of precision thickness. Forty fixed attenuators were fabricated. Target values have generally

TABLE VIII
DESIGN TARGETS FOR OPTICAL ATTENUATORS

Component	Target value (wavelength region 1.3 ±0.03 μm)
Variable attenuator	Attenuation: 0 ∼ 60 dB: step variable 0, 10, 20, 30, 40, 50 dB; continously variable 0 ∼ 15 dB
	Attenuation accuracy: less than ±5% (in dB)
	Insertion loss: less than 4 dB
	Temperature dependency: within ±0.5 dB (25 ±15°C)
	Reflected light: less than -15 dB
Fixed attenuator	Attenuation: 3, 6, 10, 20, 30 dB
	Attenuation accuracy: 3 ±1.3 dB, 6 ±1.5 dB, 10 ±1.5 dB, 20 ±2 dB, 30 ±3 dB
	Size: less than 25 ∼ 10 mmφ
	Temperature dependency: within ±1.0 dB (25 ±15°C)
	Reflected light: less than -15 dB

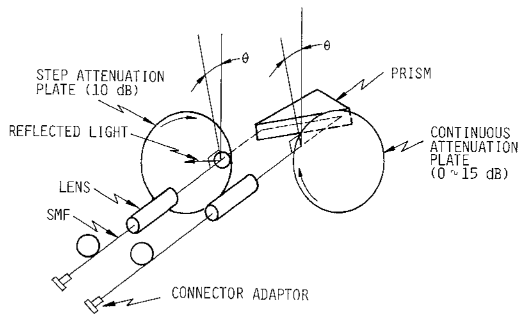


Fig. 15. Structure of variable attenuator.

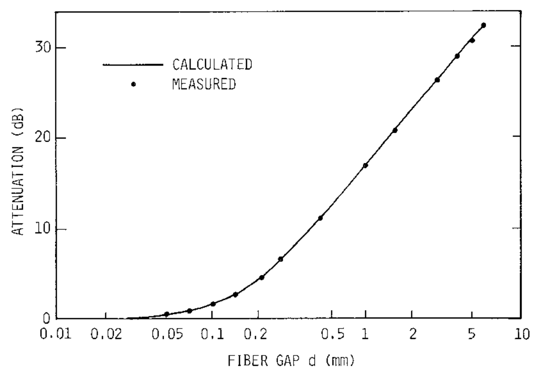


Fig. 16. Attenuation versus fiber gap.

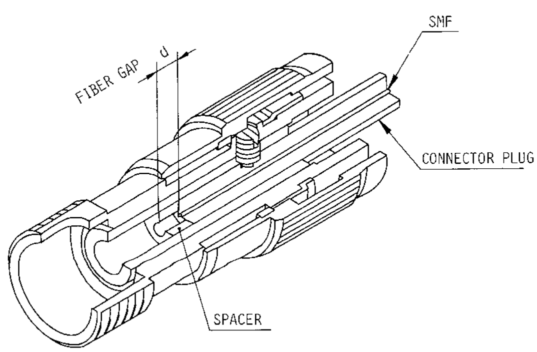


Fig. 17. Structure of fixed attenuator.

been reached, but some units were below the temperature dependency target value similar to that of the variable attenuator.

IV. Synthetic Evaluation in Field Trial

A field trial of a 400 Mbit/s transmission system using single-mode fibers has been conducted on a section (section *C*) of the 80 km long route between two electrical communication laboratories via eleven cities in the Tokyo area. Since the system configuration and the parameters of the field trial were described in a paper by Iwahashi [10], only the experimental results will be shown here.

The optical components described in Section III were installed at various points in the transmission equipment and line, as shown in Fig. 18. That is: 1) the LD module is used for electric/optical conversion in the repeater equipment (the line terminal equipment LTE and the indoor repeater equipment REP-E), 2) the connector is used at the input/output

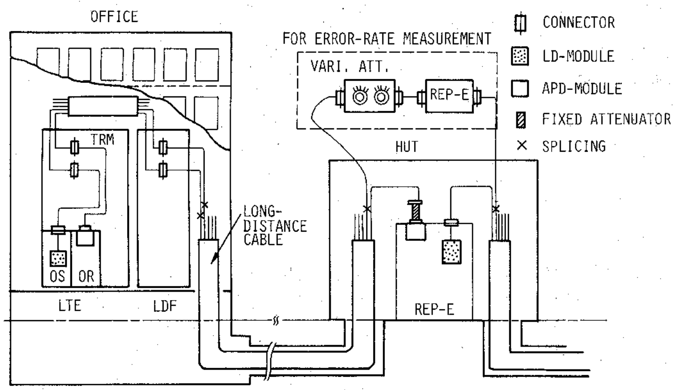


Fig. 18. Optical components installed in optical transmission equipment.

terminals of the repeater equipment and at both ends of the inter-equipment optical fiber cable which interconnects the line terminal equipment and the line distribution frame (LDF), 3) the attenuator is used for adjustment of the optical power level at the repeater input terminal and for measuring the error rate, and 4) splicing is applied to the fiber in the long distance cable.

Average fiber loss in section *C* was about 0.49 dB/km, which more than meets the requirement value of less than 0.7 dB/km. A newly developed splicing machine [69], [70] was used for SMF's. It can align fiber core axes by fine movements in vertical and horizontal directions while monitoring the output light power from one of the two fibers. Splicing loss was usually less than 0.2 dB for 100 splicing points, as shown in Fig. 19 [71]. The observed average loss for installed fibers was 0.58 dB/km including splicing loss (one splice/1.3 km) [71].

The average coupling loss of FA connectors was about 0.65 dB, including Fresnel reflection loss of 0.3 dB. This was accomplished even though the connectors were assembled by relatively inexperienced personnel. Data are shown in Section III-C.

Average optical power at the output terminal of the repeater was higher than the required value of -6 dBm for pseudo random pulse streams with 400 Mbit/s RZ (50 percent duty, 50 percent mark density). Even though mainly first-stage LD modules were installed in the repeaters, favorable characteristics were realized. By further advancing newly developed LD modules, it is expected that a higher optical output level can be easily attained for the repeaters used in the LH system.

Typical eye patterns before and after transmission over an 18 km distance are shown in Fig. 20. These patterns were observed at the light output terminal and at the input of a decision circuit in a repeater. It is apparent that no significant deterioration exists with respect to waveform distortion and jitter. An example of the bit error rate performance [65] in the LH field trial is shown in Fig. 21. This performance well exceeds the design objective.

Experimental results focusing on the transmission characteristics of the field trial are described in [65]. These measurements were taken using the SMF system's optical components, such as the FA connectors, variable attenuators, and fixed attenuators. It has been verified that there are no major problems with respect to handling, durability, and reliability. The fault location equipment described in Section II was also used in the field trial. It has been confirmed that the equipment is

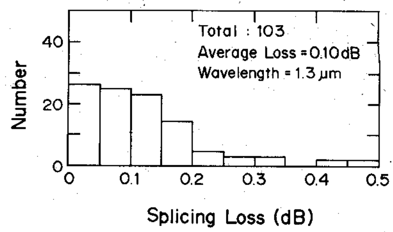
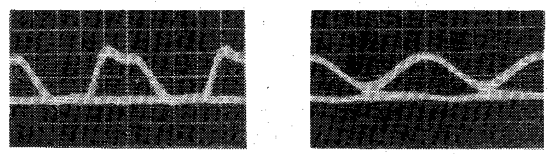


Fig. 19. Histogram of splicing loss in LH field trial.



(a) (b)

Fig. 20. Typical eye patterns (a) before and (b) after transmission over an 18 km distance (0.5 ns/div.).

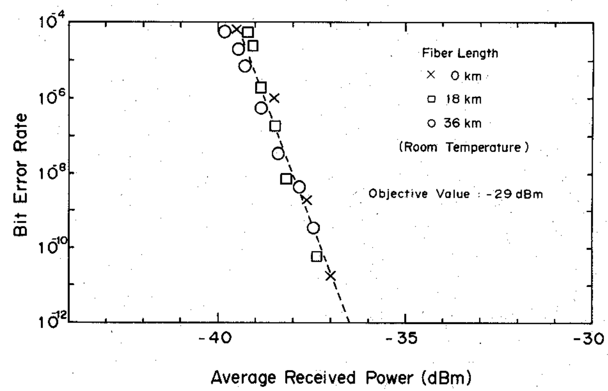


Fig. 21. An example of bit error rate performance in LH field trial.

able to locate the breaks in an SMF up to 20 km away with a resolution of 100 m.

V. Conclusion

Developmental results of single-mode fiber optical components have been explained. These components include LD modules, connectors, splicings, and attenuators which are indispensable for the construction of a large-capacity long-haul optical transmission system. These components were applied in a field trial, and it was confirmed that they have met almost all of the system requirements. It is expected that the system will enter the practical stage in the near future.

From now on, research will be directed toward reducing manufacturing costs by simplifying the assembling process, increasing the yield rate, and further improving performance.

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