FIBRE OPTIC TELEPHONE SYSTEM

FIBRE OPTIC TELEPHONE SYSTEM
OPTICAL COMPONENTS

By

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A B S T R A C T

One of the major purposes of this project was to demonstrate optical components which will be used in fibre optic distribution systems. These include the fibre itself, couplers, connectors, splices, sources and detectors. All components used are state-of-the-art, the star coupler and fusion splice technique being developed by the author during the completion of the project. The star coupler has proved to have one of the lowest insertion losses of any such component to date. Although the telephone system demonstrated has only 3 stations, very similar or identical components would be used in an expanded network.

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TABLE OF CONTENTS

ABSTRACT		iii
ACKNOWLEDGEMENTS		iv
LIST OF ILLUSTRATIONS		vi
CHAPTER		
I	INTRODUCTION	1
II	THE FIBRE general description attenuation dispersion	9
III	SOURCES AND DETECTORS light emitting diodes photodetectors	14
IV	DISTRIBUTION SYSTEMS	15
V	COUPLERS bidirectional couplers 1 to 3 star coupler splices and connectors	17
VI	FIBRE SYSTEM LAYOUT RESULTS	23
VII	EXPANSIONS ON SYSTEM power requirements increasing the number of stations	24
VIII	CONCLUSION	28
IX	APPENDIX A bidirectional theorem	29
	ILLUSTRATIONS	33-49
	BIBLIOGRAPHY	50

LIST OF ILLUSTRATIONS

FIGURE

1.	Layout of Optical Fibre Telephone System	33
2.	Central Processor for O.F.T.S.	34
3.	BNR Step Index Fibre #196	35
4.	Attenuation vs. Wavelength Graph	36
5.	Northern Telecom LED UNC-2A	37
6.	Maximum Ratings for LED	37
7.	LED Characteristics	37
8.	Wavelength Output of LED	38
9.	LED Power Output vs. Current	38
10.	LED Power vs. Temperature	38
11.	LED Power vs. Frequency	38
12.	LED Power vs. Operating Time	38
13.	Photodiode NT-D-5-1	39
14.	Photodiode Wavelength Responsitivity	39
15.	Photodiode Maximum Ratings	39
16.	Photodiode Characteristics	39
17.	Tree System	40
18.	Star System	40
19.	Bidirectional Transmission	41
20..	Biconical Taper Coupler	42
21.	Far Field Pattern from Bidirectional Coupler	43
22.	Loss Measurement	43
23.	Coupling Ratio Graph	44
24.	Bidirectional Loss Layout	45
25.	Star Coupler Schematic	46
26.	Coupler Cross-section	46
27.	Optical Fibre Connector	47
28.	(a) System Layout Results Before Connectorizing	48
	(b) System Layout Results After Connectorizing	49

CHAPTER 1

INTRODUCTION

One of the main advantages of fibre optics is the large potential increase in information-carrying capacity. Because of its higher frequency, light offers an increase of four orders of magnitude over microwave transmission. As well as this, fibre optics is advantageous for other reasons. These include crosstalk immunity, ground loop immunity, E.M.I. immunity, small size and weight, and longer repeater spacing due to the fibres low loss and wide bandwidth.

As an example of the state of the art of optical fibre communications, a system was installed in Chicago in 1977 over a ten kilometer length. It used injection lasers driven at a rate of 44.7 megabits per second. The fibre cable contained 24 fibres, each fibre having the capacity to carry 672 one way voice signals.

Many such systems have been recently built, and evaluation reports are just beginning to appear. Many areas and problems remain to be investigated. For instance, a recent article in the IEEE Journal of Cable Television points out the need for more research into optical splitters and taps. This need was one of the primary motivations for the present project.

For our M. Eng. on-campus project, my associates and I have chosen the design, assembly and preliminary evaluation of a telephone system designed for short or medium distance transmission over optical fibre.

For a successful completion of the project, this system was required to meet the following specifications:

1. Each end of a two party conversation must be able to transmit and receive simultaneously, as is the case with most public telephone systems. Such an arrangement is referred to as a duplex system.
2. This system should have most of the other characteristics of a commercial telephone system, such as:

a) there be a system of audio cues (dial tone, busy tone, ringing tone, etc.)

b) that no adjustments or technical knowledge be required of the user

c) that all of the interconnections be made automatically and be based on a simple number system

d) that all conversations be inaccessible to other parties

3. The system should be compact, and rely on portable power supplies at each station.
4. The system should make use of optical (as opposed to electrical) types or splitters, employ fibres bidirectionally (rather than using separate fibres for transmitting and receiving), and have all signals carried over a single fibre (i.e. a multiplexed system).
5. Due to the varying numbers of taps, different positions of stations, etc., the system should be able to handle a 60 dB optical loss between any transmitting and receiving points. As well, the receivers must be able to handle multiple signals differing by up to 40 dB in optical strength.
6. Although only 3 stations are required to demonstrate a basic tele-

phone system, the parameters and design specifications are to be based on a system with up to 100 stations.

7. It should be possible to change cable lengths and interchange stations without extensive electronic adjustments.

The format of the optical signals was chosen to be analog. This was done for simplicity and because of numerous technical problems encountered when trying to use a clock sync signal over the same link as the data, and over varying lengths of travel. The analog electrical data signals would intensity modulate the light from a suitable optical source. This is different from amplitude modulation in that the modulated intensity can never be less than zero. If all of the optical sources are to operate on the same optical wavelength, then the multiplexing must be done on the electrical data signal. This is done by using radio frequency subcarriers of different frequency as the different data channels. For the sake of simplicity, the voice signals would be amplitude modulated onto the appropriate RF subcarriers. Because of the availability of off-the-shelf components for the citizen's band frequency range (26.5 MHz - 27.3 MHz), the subcarrier frequencies were chosen from this range.

Once the subcarrier multiplexing had been chosen, a number of solutions become possible to the problem of establishing a conversation link between stations. One solution is to have each station contain the logic necessary to establish a link, provide the audio cues, etc. and the link is made by the station initiating the call. For an N station system, this can be implemented by each station containing its own unique transmitting subcarrier channel but N possible receiving channels. The caller then receives on the called party's transmitting channel and tells the called party which receiving channel he should use. An N transmitter/1 receiver station cannot be used since a busy signal could not be produced.

Another approach is to use a separate "central" switching station where the links are made. The caller then dials the central station, identifying the called party and the central station activates the appropriate switched connections to link the caller and the called party. It is likely that there would be enough optical reflection in the system such that a significant fraction of the signal transmitted from a station will return to the receiver. If the receiving channel and transmitting channel for each station are the same, this reflected signal could swamp out the conversation. This could be avoided by using a talk/listen switch, but this would violate requirement #1. Instead, separate transmit and receive channels could be used. This is the case with the finished system. Now, 2N subcarrier channels are needed for an N station system.

This second approach was chosen for a number of reasons. With the central processor (C.P.) system, extra stations can be added without changing the existing stations. The individual stations are also much simpler, and this system as a whole is more easily adaptable for linkup with a commercial telephone system. Also, it is the cheapest to produce.

This C.P. version is similar to a commercial telephone system. On the commercial system, the various "stations" produce different voice signals on different wires leading to the central switching unit. These signals are all in the same frequency range (audio baseband), and the central switching unit puts the voice signals onto the appropriate outgoing wire. In this optical system, the different voice signals occupy different frequencies, but all on the same "wire". The C.P. then switches the voice signals onto the appropriate outgoing frequency.

The present system used near infrared LED's as the optical source. Either PIN photodiodes or avalanche photodiodes could be chosen as the detector. To avoid the high voltage power supplies required by an avalanche photodiode, PIN photodiodes were chosen.

Initially, multifibre optical cables were to have been used because of the availability of couplers and the ease of making splitters. However, the recent development of fused splitters and couplers for single fibres offer lower loss and more flexability in splitting ratios. For these reasons, single fibre cable was used. Because of the short distances over which this cable would be used, dispersion is not a problem. Therefore, the choice between graded index or step index fibre was made only on availability.

There are three possible layout configurations for the optical cable: the star, the tree (main trunk) or a combination of both.

In the star system, the losses increase linearly with N and all of the signals are roughly the same amplitude at a given receiver. However, the layout is not very flexible, and requires a larger quantity of fibre than the other two layouts.

The tree, or main trunk configuration requires the least amount of cable. However, the dynamic range of the signals and the loss at the weakest station increase exponentially with N, due to consecutive tapping.

Combining both the star and the tree configurations, which is normally done for CATV, most of the advantages of each can be made. This was the configuration chosen.

As shown in Fig. 1, the geometry of the fibre in this layout takes the shape of a multi-branched "Y". The central processor which does the switching between the various subcarriers is situated at the base of the main arm of the "Y". A single fibre enters each of the telephone stations and the central processor. Inside these units, a fused fibre coupler divides the light into two separate fibres. At the end of one of these fibre segments is an LED. Suitably modulated light is produced here and propagates out through the 2-1 splice into the tree. The other fibre segment runs into a photodiode. These detect the signals that have been modulated onto the light coming off the tree.

Each telephone station has an optical receiver consisting of a photodiode followed by an A.M. radio receiver and an optical transmitter consisting of an infrared LED at the output of an A.M. radio transmitter. A telephone station identifies the station to which he wants to speak by means of an ordinary telephone dial switch. This switch is used to interrupt the subcarrier coming from the calling station. The C.P. senses these interruptions and makes the necessary switches connections.

The central processor also uses a photodiode in its optical receiver and an LED in its optical transmitter. However, here there are N radio receivers and N radio transmitters interfacing with these opto-electronic components. In the C.P., there is a receiver/transmitter pair corresponding to each of the N stations. The C.P. receiver for a station is tuned to the subcarrier that the station transmits on and its C.P. transmitter is tuned to the subcarrier that the station receives on. The central processor is shown in Fig. 2.

Between the radio receiver bank in the C.P. and the radio transmitter bank, there is a switching network. When one station dials the phone number of another station, the C.P. counts the subcarrier interruptions. With this information, the proper audio switch is closed to connect the audio output of the C.P. receiver corresponding to the calling station with the audio input of the C.P. transmitter corresponding to the called station. Another switch is simultaneously closed to connect the reverse path. The same control signal that operates the audio switches also turns on the C.P.'s transmitter to the called party. When the called party's phone senses this subcarrier turn-on, the phone starts ringing. When the called party answers his phone, the ringing stops and two way conversation takes place through the C.P. As well as the basic network of audio switches, the C.P. also contains the TTL logic controlling the switching and the various audio cues (dial tone, busy tone, ring tone). This logic is such that these tones are heard under the same circumstances as in a commercial telephone system.

The work on this project was divided into three sections:

(1) switching logic and peripherals - J. Goodwin

(2) optical fibre, splitters, connectors, sources and detectors - G. Duck

(3) analog electronics - A. Jurenas

Parts 1, 2 and 3 are described in detail in the reportssof Goodwin, Duck and Jurenas. The system with three telephones, C.P., power supplies and interconnections is operational, and is now undergoing detailed evaluation. The latter work is being done by V. Tzannidakis, who will report on it at a later date.

CHAPTER 2

THE FIBRE

(i) General Description

The optical fibre chosen for the system was a glass single strand multimode step index fibre BNR 196. Its 100 μm diameter core and numerical aperature (N.A.) of 0.26 give it a large light-carrying capacity in comparison with other glass fibres available (see Fig. 3). The major advantage with this fibre, however, is that low loss taps, splitters, splices and connectors can be made with relative ease. Other fibres were examined, but were rejected for the following reasons:

Fibre bundles (glass)	- ends must be polished; taps and splitters are hard to make and have high loss; expensive.
Graded index single strand glass fibre	- this type of fibre does not transmit as much light as step index fibres and would only be used if the system became dispersion limited.
Plastic fibre	- inexpensive, but has high attenuation (>400 dB/km)

The BNR 196 fibre was manufactured using the CVD process, starting from a pure silica tube and depositing a core doped with germanium to achieve the changes in the index of refraction. The collapsed preform was then pulled into a fibre with an outside diameter of 150 ± 2 μm and coated with "hytrel"[1] by an extrusion process bringing the total diameter to approximately 0.5 mm. The plastic jacketing provides the fibre with bending resilience, but its tensile strength comes almost entirely from the glass itself. This fibre can typically withstand a bend to a diameter of about 2 mm and a tensile force of up to 12 lbs.

(ii) Attenuation

One requirement for the system was that the fibre should have a relatively low loss or "attenuation". Attenuation, which is a function of wavelength, is usually given in decibels per kilometer and is defined by the following equation:

$$\text{ATTEN}(\lambda)\ (\text{dB/km}) = -\frac{10}{L} \log \frac{I_L}{I_0}$$

where - L is the length in km

- I_0 is the input light intensity
- I_L is the output intensity after a distance L
- λ is the wavelength of the light

This definition, however, is not quite complete. There are some conditions of measurement which are not stated, as a standard definition or measurement technique for attenuation has yet been adapted. Each manufacturer uses a slightly different method making any comparisons difficult. There are several problems, one being that attenuation is a function of the light launching conditions. Thus, fibre loss depends on what is used as a source, whether it is an LED, laser diode, gas laser or even

1 A copolyester elastomer from Dupont

on which particular LED or laser is employed. It has been found that loss can vary up to 1dB/km by using LEDs having different radiation characteristics. Part of the reason for this variation is that there is a dependence of attenuation on the launching numerical aperature with the higher angled light having the greater loss.

The other major problem comes from the fact that the loss of a fibre appears to be different depending upon the location of the fibre in the system. A length of fibre will seem to have a higher attenuation if placed near the light source as compared to a location further down in the link. This is due to a disproportionately large loss of leaky modes and higher order modes in the first few hundred meters from a source. After this distance, which is called the "equilibrium length", the transmitted light begins to vary exponentially as a function of length. Therefore manufacturers quote an "equilibrium attenuation value" which is defined as the loss in the fibre after the "equilibrium length". Corning Glass Co. achieves this measurement by using a gas laser, underfilling the numerical aperture of the fibre and comparing the light output after a long length (over 1 km) to the input. BNR does this by inserting a "pigtail" fibre (which is longer than the equilibrium length) ahead of the fibre to be measured, launching into the pigtail and comparing the long length output to that from a point one meter downstream from the connection (a fusion splice) between the two fibres. (Developed during the summer work term of 77 at BNR). Using BNR's measurement technique, the step index fibre BNR 196 has an attenuation of 4.5 dB/km at 840 nm. Its "spectral" attenuation curve is also shown in Fig. 4.

Before finishing this section it should be mentioned that some of the problems incurred in measuring fibre attenuation, such as type of source used and the effect of the fibre equilibrium length appear again when measuring losses in splices, connectors, and couplers. For example, the loss due to a splice near a source will appear greater than one further down the fibre link because of the loss of leaky and higher order modes. In designing or expanding a system this should be taken into account.

(iii) Dispersion

Dispersion is the broadening in time of a light pulse as it travels down a fibre. (The equivalent notion in the frequency domain is fibre bandwidth). There are two types of dispersion; "modal" dispersion, arising because of different path lengths of the light entering the fibre and "chromatic" dispersion which is caused by the different transmission velocities of light of different wavelengths. The two are combined to give a total pulse broadening of:

$$T_{tot} = (T^2_{modal} + T^2_{chromatic})^{1/2}$$

The modal dispersion, T_{modal}, is usually the quantity which is experimentally measured and is defined as the FWRMS (full width root mean square) of the output pulse from a length of fibre when the input pulse is a quasi delta-function (in time domain) from a laser having a narrow spectral width. It is normally given in nanoseconds per kilometer, however, it does not always vary linearly with length. Depending on the loss and the amount of mode mixing, dispersion can increase with fibre length according to $T = CL^Y$ where Y is typically between 1/2 and 1. The step index fibre used in this project has a modal dispersion of approximately 20 nsec/km.

The chromatic dispersion can be accurately calculated theoretically. The broadening of pulses varies directly with the width of the band of wavelengths transmitted. For an LED of spectal width 400 angstroms, the chromatic dispersion is 2.7 nsec/km. A typical laser diode has a width of only 20 angstroms and would reduce this dispersion by a factor of nearly 20.

CHAPTER 3

SOURCES AND DETECTORS

(i) Light Emitting Diodes

The LED's used in this project are BNR high radiance infrared diodes having current confined double heterostructure emitting through the N-side. The chips are nominally 0.5 mm square with the light being emitted from a 75 μm diameter surface at the bottom of an etched hole. They were supplied with the hytrel-jacketed fibres attached. Typically 300 mW of light is collected by the fibre when run continuously at 150 mA. However, because of the speed of the device the relative power output at 27 MHz is reduced by a factor of approximately 2 dB. Fig. 5 through 12 give the specifications and characteristics of the devices.

(ii) Photodetectors

All four detectors used in the stations were BNR silicon P-I-N photodiodes. The diameter of the photosensitive surface is 125 μm. They feature small chip capacitance (0.2 pF), fast response speed (<4 nS rise and fall time 10-90%) and high quantum efficiency (85% at λ = 840 nm). The device is illustrated in Fig. 13. Other characteristics are shown in Fig. 14 through 16.

CHAPTER 4

DISTRIBUTION SYSTEMS

In communication networks there are two types of configurations being used to distribute information. One is the "tree" distribution system which involves tapping power from a main trunk line using access couplers and the other is the "star" system which employs a star coupler to split the optical power equally into many arms at some point. It was decided that for this project, both types of couplers should be demonstrated since each has its advantages and would probably be used if the system were expanded to one hundred stations. The tree system is effective when the excess loss at each junction, excluding furcation loss, is small. It has the disadvantage, however, of forcing stations to be equipped with a wide dynamic range A.G.C. in order to handle both strong signals from adjacent stations and weak signals from remote stations. The star system, on the other hand, has the advantage that it can service many more stations than the tree system under a given sensitivity limit.[2] although it generally uses more fibre.

The following example will illustrate some of these points: A given receiver can withstand a loss of 40 dB. Using the tree system, (refer to Fig. 17), if each station taps off one tenth of the power being transmitted down the main trunk line and assuming an excess loss

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2 The statement is true for large enough sensitivity limits

of X dB at each tap, the number of stations N which can be served is:

$$N = \frac{30}{10 \log \frac{9 - X}{10}}$$

For an insertion loss X of 0.5 dB N < 65.

Now using the star system (Fig. 18) and with the same 40 dB limit, the number of stations which can be served is:

$$N = 10^{\frac{40-Y}{10}}$$

where Y is the insertion loss at the star coupler.

For a coupler loss Y of 1.5 dB, N > 6300.

CHAPTER 5

COUPLERS

(i) Bidirectional Couplers

For bidirectional transmission on a single multimode fibre, it is desirable to be able to input most of the light from the source fibre to the main trunk fibre and also to be able to receive most of the light from the trunk fibre at a detector. There are, however, limitations imposed by the brightness theorem. For a passive system which uses a lambertian source and fibres of the same type (size and NA), the best that can be achieved in the above bidirectional situation (Fig. 19) is a total one-way link loss of 6 dB (assuming no fibre loss). This corresponds to the situation in which one half of the light in the source fibre enters the trunk fibre and one half of this light is detected through the detector fibre at the opposite end. The proofs of these statements are given in Appendix A.

A recently developed fused biconical taper coupler[3] for single strand multimode fibres was the device used for the optical Y's. In essence it is a tap or access coupler. The device, as shown in Fig. 20, is fabricated by wrapping the tap fibre around the trunk fibre and then fusing and pulling the tapers simultaneously using an oxy-butane microtorch. The biconical tapered section has a total length of approximately 1.0 to 1.5 cm. Qualitatively the principal of operation is

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3 B.S. Kawasaki, Private Communication and Applied Optics <u>16</u>, 1794, (1977)

as follows. Most of the light which is initially launched as guided modes in the main trunk fibre radiates out of its core in the narrowing taper region and is transformed into cladding modes of both fibres. The light propagates to the region of expanding tapers where it is converted back into guided modes to propagate in the cores of the individual fibres. Some light, however, is lost to the surroundings and is referred to as the coupler's insertion loss. Figure 21 shows the far-field pattern from ports 3 and 4 of Fig. 20 when a HeNe laser is focussed into port 1. If the couplers are made with step index fibres, higher order modes are predominately tapped off. For graded index fibres the transferred light has a more uniform mode structure.

To evaluate the couplers, the measurement set-up in Fig. 22 was used. The long input length was necessary in order to eliminate any effect on the coupling ratios and efficiencies by leaky and higher order modes which only travel a few hundred meters, or less if stripped out by splices and connectors. Port 1 was attached to a typical BNR LED (840 nm) and the outputs from ports 3 and 4 were monitored while the coupler was being made. A typical result is shown in Fig. 23 where the horizontal axis consists of steps of increasing tapering or more specifically time into the manufacturing process. The vertical scale is linear and was labelled to read 1.0 for port 4 and 0.0 for port 3 before the coupling commenced corresponding to the situation which occurs when all of the light was being transmitted through port 4. As can be seen there is a maximum amount of light which can be tapped out of the trunk fibre. This amount varies for different couplers and different types of fibres but for the step index fibre used in this project this maximum transfer occurs when the ratio of light in the trunk fibre (port 4) to the tapping fibre (port 3) is approximately 2:1. Any further heating results in extra losses from both arms. It is at this point of maximum transfer that the signals can be optimized in a symmetric bi-directional link such as in Fig. 24. The couplers have an insertion loss of 25% (1.5 dB) when they are located at the end of a long fibre but 40% (2.2 dB) when situated near the source (at the beginning of a fibre section), due to the extra loss of leaky and higher order modes. This increased loss of 15% when the coupler is close to a source is misleading because although it is lost at the coupler, it would have been lost if the length of fibre following the coupler was greater than the fibre's equilibrium length, or if there were splices and connectors after it.

Thus in a system such as that illustrated in Fig. 24, the loss in the link from station 1 to station 2 or vice versa would be:

$$\underbrace{(10 \log 2/3 + 2.2)}_{\text{Loss in coupler 1}} + \underbrace{(10 \log 1/2 + 1.5)}_{\text{Loss in coupler 2}} = 10.2 \text{ dB}$$

In this bi-directional system, one has a choice whether to attach the source to the main trunk fibre and receive on the tapping fibre or vice versa. However, the couplers preferably excite higher order modes which have an attenuation of 0.5 dB/km higher, therefore having the LED on the main fibre is an advantage.

(ii) 1 to 3 Star Coupler

A new low loss star coupler was developed for the project and introduced into the system in order to demonstrate the second major coupler used in distribution systems. It splits the signal from a single fibre into three approximately equal signals. Figure 25 shows a schematic of the coupler. Three fibres were first twisted together, fused and tapered. Then all three were cleaved together at a location in the tapered region where the diameter would match that of a single untapered fibre. The final step was to fuse the three tapered fibres to the single fibre. The coupler was protected by suspending the joint in air across a gap.

The loss of the coupler when used as a splitter (i.e. going from the main fibre into the three ports) is typically between 0.9 and 1.5 dB. This coupling is much better than one would first expect since it appears that the cores of the three tapered fibres would not cover the core of the single untapered fibre sufficiently and that the packing fraction loss alone would be greater than 1.5 dB. However, because of the taper the acceptance angle of the three fibres is increased and even some of the light which gets into the cladding will be captured by the cores in the up-tapered region.

When the coupler is used in the opposite direction as a combiner, that is from the three fibres into the single fibre, the losses are higher. This is due to theoretical limitations derived from the brightness theorem as previously mentioned. With a lambertian source and the same fibre for all arms, the best result that can be achieved when going from three fibres into one is to couple only one third of the light from each into the single fibre. (see reference 1). Indeed this has been observed with the combiners developed for this project. Approximately one third of each is collected, minus a small amount due to an insertion loss of about 1 dB. Thus there is a total loss of nearly 6 dB from one of the three to the main fibre. Most of this light is lost in the down-tapered section. As a combiner, the inputs to the main trunk fibre from each of the three feeder fibres are approximately equal (within 0.5 dB of each other).

(iii) Splices and Connectors

Throughout the project many fibre to fibre splices have been necessary. A tool for fusion splicing fibres was developed which first aligns the fibres and butts them together with a small amount of axial pressure between them. They are then fused together with a micro-torch and protected thereafter with either heat-shrink or metal tubing. The loss of these splices as explained earlier in Chapter 1 depends upon its location. In a long section of fibre (greater than the equilibrium length) they appear to have a loss of 0.3 ± 0.1 dB. If the same splices were measured on a short length close to a source they would average $1.0 \pm .2$ dB.

The connectors used in this project are BNR #C-20 illustrated in Fig. 26. Each fibre is contained within and protected by a stainless steel plug. The plugs are accurately aligned in a stainless steel bulkhead receptacle. The fibre ends are slightly recessed from the mating ends of the plugs to prevent fibre-to-fibre contact in the mated condition. The average loss for these connectors is 1.0 dB.

CHAPTER 6

FIBER SYSTEM LAYOUT RESULTS

The optical fibre system was assembled in the following order:

1. Four bidirection couplers were made with 1 meter of fibre for both the source and detector arms and 20 meters for the main trunk arms.
2. LED's and detectors were attached to all four couplers.
3. The 1 to 3 star coupler was then made with the main trunk arms of the bidirectional couplers.
4. Four connectors were put in approximately 1 meter from the bidirectional couplers on the main trunk fibre.

Figure 28 shows the system and the received optical power levels in both directions prior to connectorizing the link. Slight inequalities in these levels are mainly due to differences in the LED outputs.

Figure 29 shows the system again after connectorizing. LED 1 has also been changed.

CHAPTER 7

EXPANSIONS ON SYSTEM

(i) Power Requirements

The greatest limitation on expanding both the number of stations and the distance between stations is getting enough light from source to detector. There are several ways of doing this. The first method is to increase the input power by using a laser diode instead of an LED. This will give a gain of close to an order of magnitude depending upon the particular fibre being used. Secondly, on the detector side, a change can be made from a PIN to an APD (avalanche photo-diode). At the same operating speeds the background noise in an APD is lower than a PIN by a factor of 10. Also in any expansion scheme, digital transmission should be used because of its greater tolerance of noise and the ease with which digital pulses can be detected and regenerated.

Another method of increasing the power reaching the detector is to lower the fibre loss. Fibres can be bought now with a loss of less than 3 dB/km at 840 nm. In the near future it is hoped that losses will be typically around 1.0 dB/km when the industry moves toward 1.3 μm. Furthermore, with the coming of laser diodes at these higher wavelengths, fibre dispersion will no longer be a problem.

Without going to higher wavelengths and for distribution systems where dispersion is of secondary importance to power, a gain could be made by using plastic clad silica (PCS) fibre. It has a pure fused silica core with a coating of low index silicone resin serving as the cladding. This gives a step index fibre with a numerical aperture of 0.40 and an increase in launched power of approximately $2.37 = \left[\left(\frac{0.4}{0.26}\right)^2\right]$ over the fibre used for this project. Silicone clad fibre, a member of the PCS family has been made with a loss of less than 3 dB/km and a dispersion of 10 nsec/km at 840 nm. These fibres are also inexpensive to make, since pure silica rods can be bought and the manufacturer has only to draw and coat the fibre. Another advantage of this fibre is that very low loss taps and splitters can be made very easily. Access couplers, which tap off up to 1/3 of the light from a main trunk fibre, can have an insertion loss of less than 0.1 dB. There are, however, two minor disadvantages with this type of fibre. One difficulty occurs in preparing the fibre ends. A chip on the endface will cause scattering of light. Previously, in other types of fibre, this did not happen if the chip occured in the cladding and not in the core. Along with this problem is that of the necessity of surface cleanliness when making splices or couplers. Dirt or finger oil will cause loss since it will act to give a boundary to a higher index.

(ii) Increasing the Number of Stations

The distribution network can easily be expanded since star couplers have been made with up to 19 fibres and the insertion losses when they are used as splitters are below that of the 1 to 3 couplers used in this project. This is due to a better packing fraction. When used as a combiner, however, only 1/19 of the light from each feeder is accepted by the main trunk fibre. In order to improve this it is necessary to use smaller input fibres compared with the main trunk. This is possible when laser diode sources are used for they have an emitting area with linear dimensions of loss than 15 μm.

Thus couplers can be made to handle an increased number of stations. However, there is still the problem of multiplexing. Our system is frequency multiplexed using a limited number of CB radio frequencies. Each station uses two of these frequences. The number of stations could be doubled still using these CB frequencies if each station only had to use one. This could be done providing that the signal reaching the stations from the C.P. (central processor) was much larger than the back-reflected light from the bi-directional couplers, splices and general fibre scattering. The ratio of the power coupled into the forward direction to that which is coupled to the backward direction is called the directional isolation of a bi-directional coupler. The couplers used in this project have an isolation of approximately -45 dB when both output ports are immersed in an index-matching oil. With a long fibre spliced to the main output port and the unused output port kept in oil, the isolation decreases to -40 dB due to fibre backscattering. Finally, there is another promising method of increasing the capacity of fibre optic system currently being researched. It is called wavelength division multiplexing (WDM) and uses sources of different light wavelengths usually separated by greater than 10 nm. Some problems still exist, such as lowering the insertion loss of coupling several fibres onto one fibre and then decoupling the separate wavelengths. Another problem, that of crosstalk will be reduced as the spectral width of the sources improve.

CHAPTER VIII

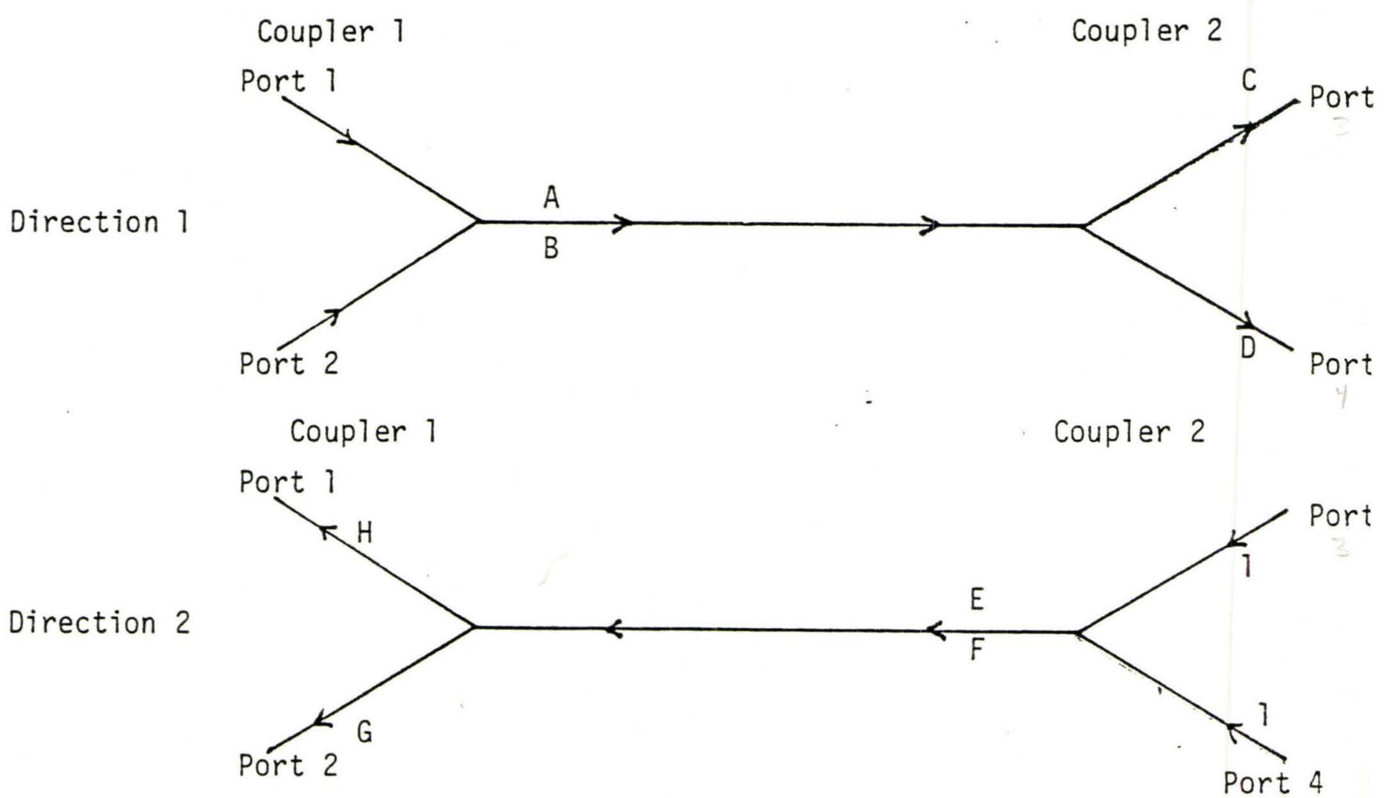
CONCLUSION

The optical fibre system has been successfully demonstrated. All optical components used have been of top quality and improvements would be negligible. For expanding the system, suggestions have been made which may require slightly different optical components, however, the general principles and techniques will still be used.

APPENDIX A

Bidirectional Theorem : In a symmetric bidirectional fibre optic link (i.e. same loss in both directions) using lambertian source of the same spectral output and fibre of the same type, size, and N.A. in all couplers, the minimum one way loss is 6 dB.

Proof : Consider the completely general bidirectional link shown below:



where $0 \leq A, B, C, D, E, F, G, H \leq 1$

Suppose the couplers are such that an input of 1 into port 1 of coupler 1 transmits a fraction A into the main trunk. Similarily an input of 1 into port 2 of coupler 1 transmits a fraction B into the main trunk, an input of 1 into port 3 of coupler 2 inputs E into the main trunk and an input of 1 into port 4 inputs F into the main trunk.

Suppose also that an input power of 1 into the main trunk in the direction 1 is split into the fractions C into port 3 and D into port 4. In direction 2 an input of 1 into the main trunk transmits H into port 1 and G into port 2.

The following is a list of the four possible bidirectional links:

Case	Direction 1		Direction 2
1	(Port 1 to Port 3)	with	(Port 4 to Port 2)
2	(Port 1 to Port 4)	with	(Port 3 to Port 2)
3	(Port 2 to Port 3)	with	(Port 4 to Port 1)
4	(Port 2 to Port 4)	with	(Port 3 to Port 1)

It is required to prove that:

In case 1: AC (=FG by symmetric requirement) $\leq 1/4$ since ($-10 \log 1/4 \approx 6$ dB)

2: $AD = EG \leq 1/4$

3: $BC = FH \leq 1/4$

4: $BD = EH \leq 1/4$

The proof is going to require the use of the following 3 sets of equations:

1. $C+D \leq 1$ by conservation of energy

2. $G+H \leq 1$

3. $A+B \leq 1$ (see reference 3)

4. $E+F \leq 1$

5. $A \geq H$

6. $B \geq G$ assumed without proof

7. $E \geq C$

8. $F \geq D$

Now, from 1 $C+D \leq 1$

$$CD \leq C(1-C) = C-C^2$$

$$= C-C^2 + 1/4 - 1/4$$

$$= -(C^2-C+1/4) + 1/4$$

$$= -(C - 1/2)^2 + 1/4$$

9. $\leq 1/4$

Similarily:

10. $HG \leq 1/4$ using 2

11. $AB \leq 1/4$ using 3

12. $EF \leq 1/4$ using 4

Case 1. $(AC)(FG) \leq (AE)(FB)$ from 6 and 7

$= (AB)(EF)$

$\leq (1/4)^2$ from 11 and 12

but $AC = FG$ for symmetric transmission

$\therefore ACFG = (AC)^2 = (FG)^2 \leq (1/4)^2$

$\therefore AC = FG \leq 1/4$

Case 2. $(AD)(EG) \leq (AF)(EB)$ from 8 and 6

$= (AB)(EF)$

$\leq (1/4)^2$ from 11 and 12

but $AD = EG$ for a symmetric link

$\therefore AD = EG \leq 1/4$

Case 3. $(BC)(FH) \leq (BE)(FA)$ from 7 and 5

$= (AB)(EF)$

$\leq (1/4)^2$

$\therefore BC = FH \leq 1/4$

Case 4. $(BD)(EH) \leq (BF)(EA)$ from 8 and 5

$\leq (AG)(EF)$

$\leq (1/4)^2$

$\therefore BD = EH \leq 1/4$

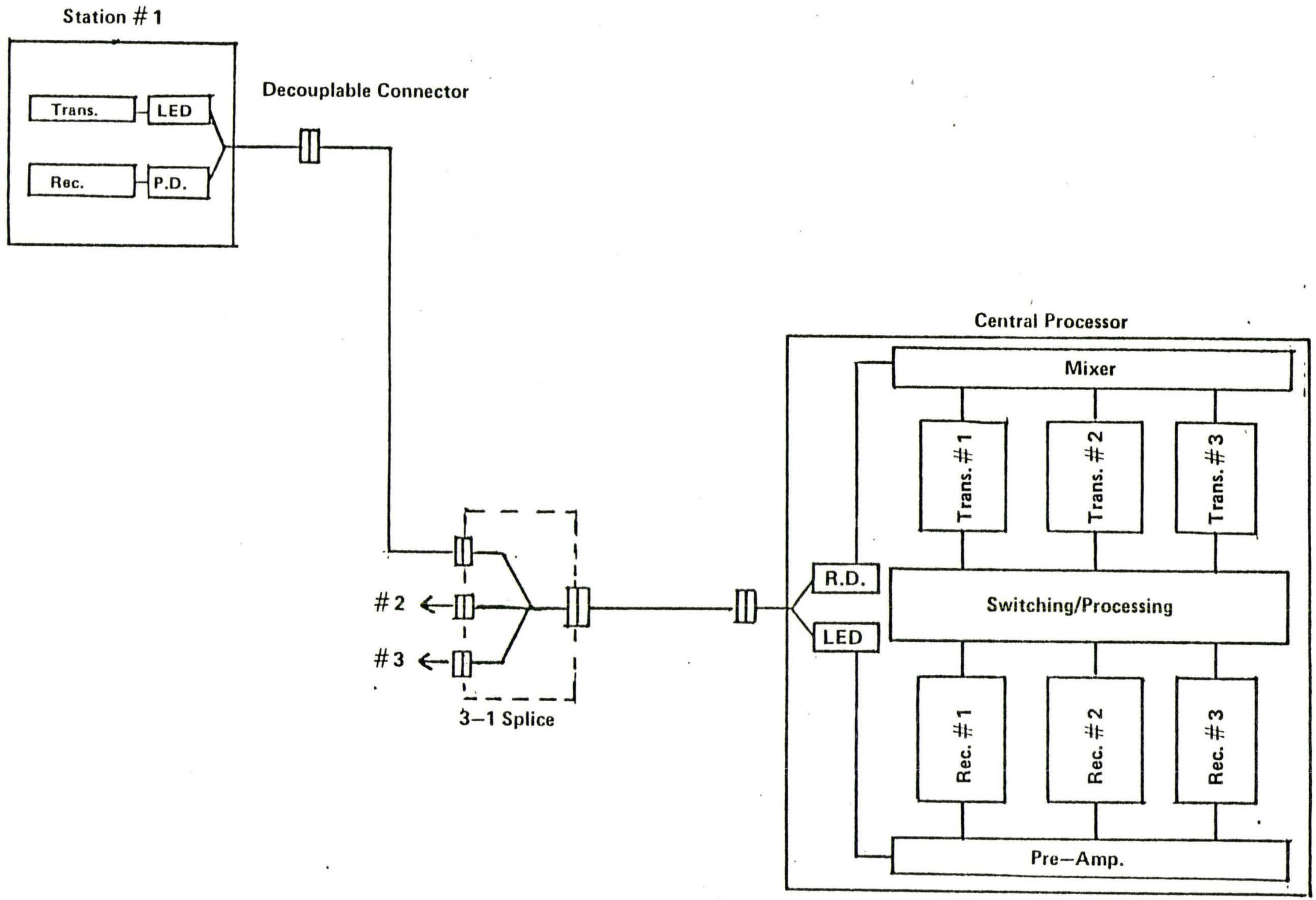


Figure 1 Layout of Optical Fiber Telephone System

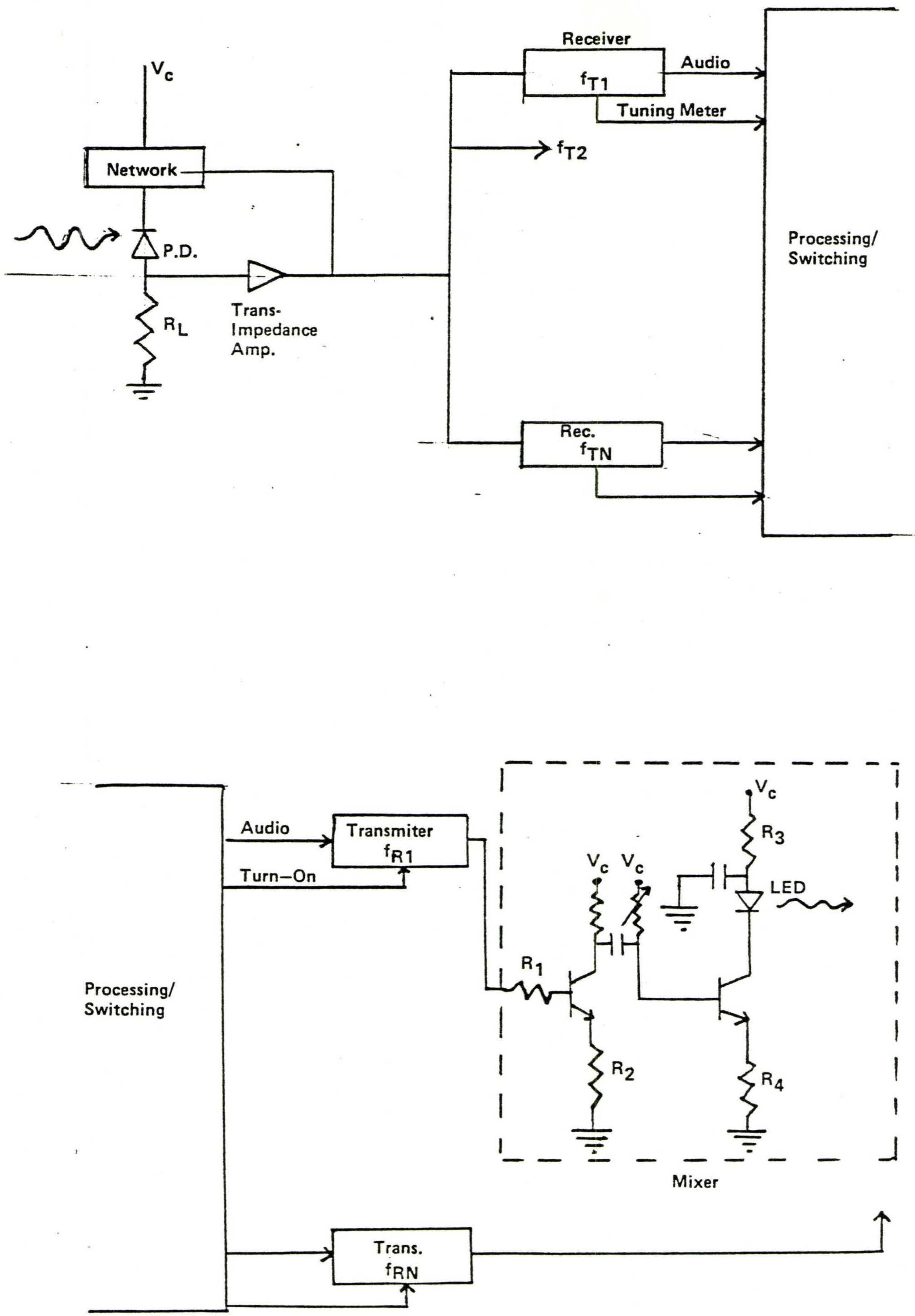


Figure 2 Central Processor For O.F.T.S.

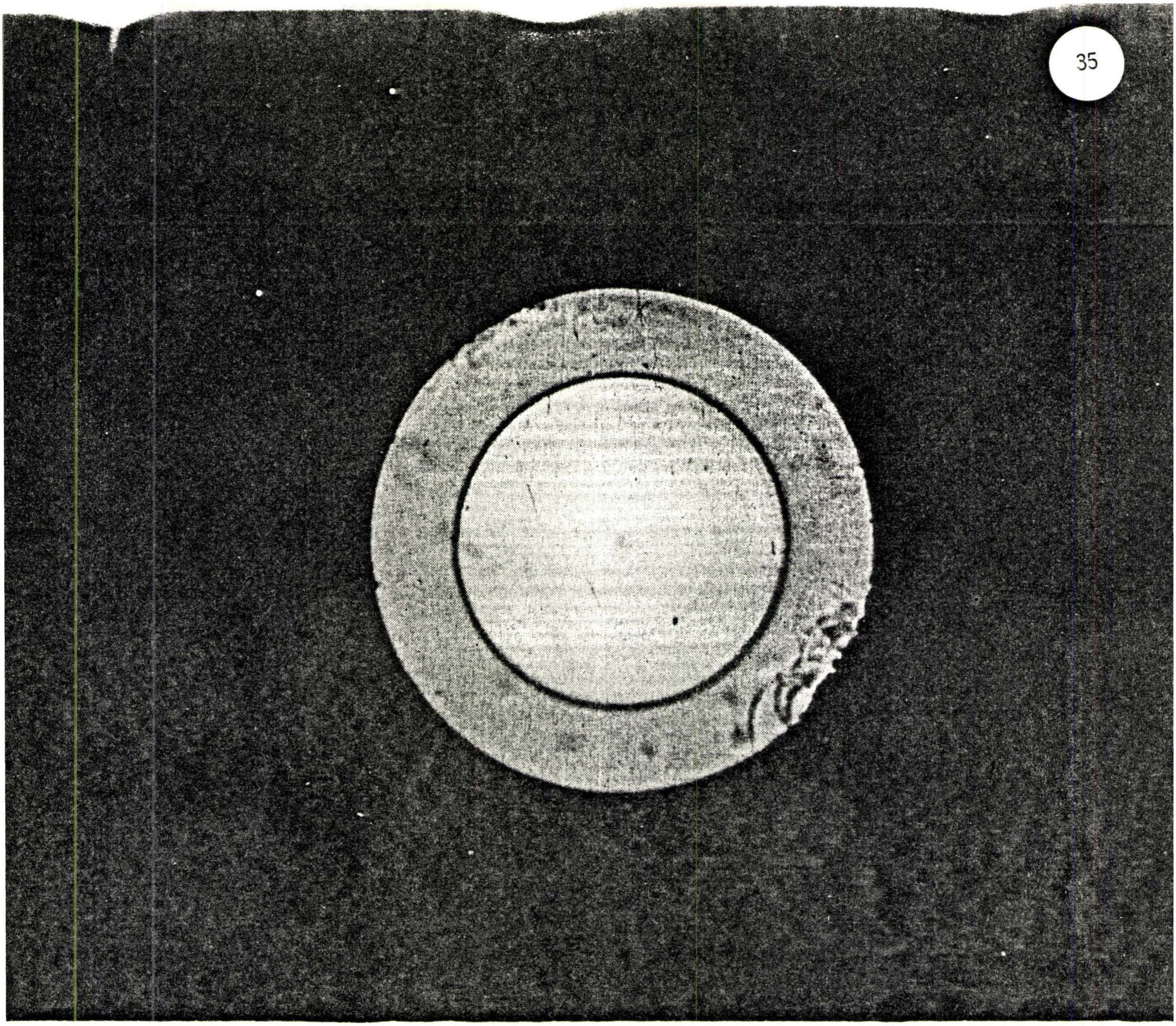


FIG.3

BNR STEP INDEX FIBER #196

OUTSIDE DIAMETER 150μm

CORE DIAMETER 100μm

NUMERICAL APERATURE 0.26

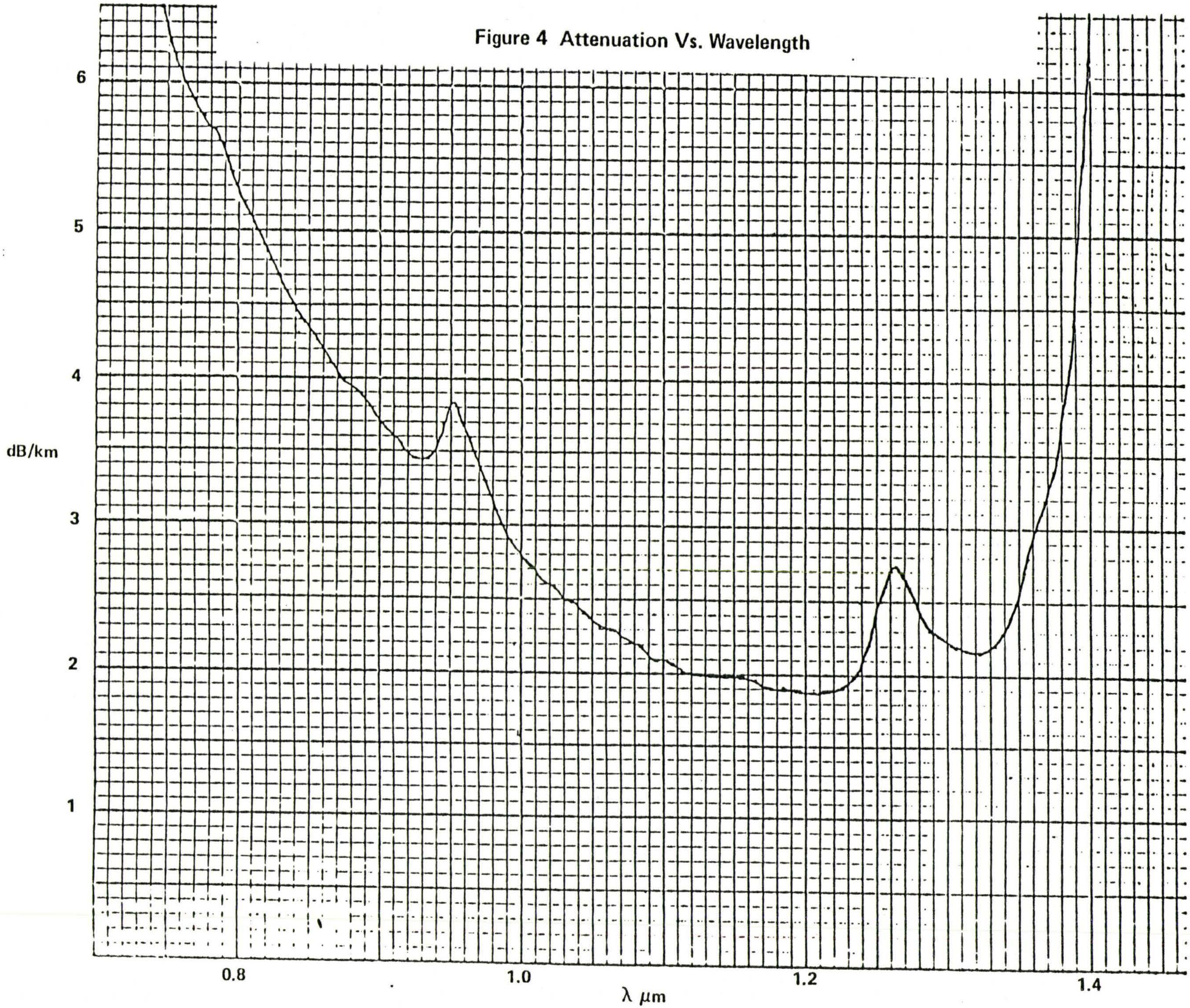
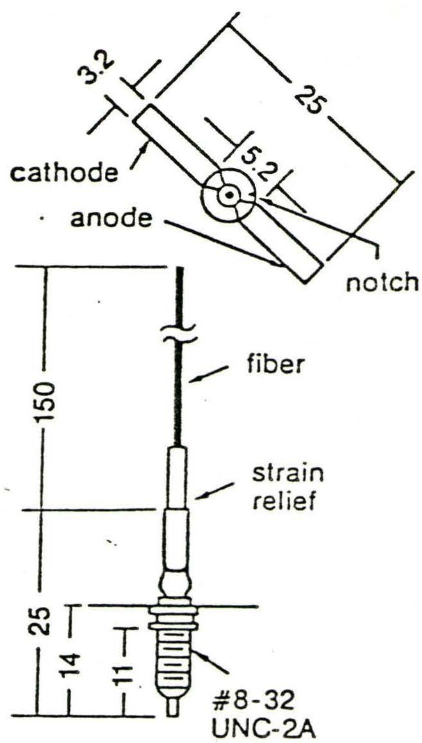


Figure 4 Attenuation Vs. Wavelength

Figure 5



dimensions in mm

Figure 6

MAXIMUM RATINGS ($T_A = 25°C$)	
Forward current-continuous	300 mA
Forward current-pulsed (1.0 μs pulse, 10^5 pps)	1 A peak
Reverse voltage	1.5 V
Operating and storage junction temperature range	−40 to +85°C

Figure 7

LED CHARACTERISTICS ($T_A = 25°C$)

	Min	Typ	Max	Unit	Test Condition
Radiant intensity (on axis)	2	3		mW/sr	$I_f = 150$ mA
Radiance	44	66		W/sr/cm²	$I_f = 150$ mA
Peak emission wavelength		830		nm	$I_f = 100$ mA
Spectral width @ half intensity		40	45	nm	$I_f = 100$ mA
Forward voltage		1.7	1.9	V	$I_f = 100$ mA
Reverse breakdown voltage		1.5		V	$I_R = 10\ \mu$A
Light turn-on and turn-off time (10-90%)		14	19	ns	50 Ω system, 5 mA dc bias
Bandwidth – Optical power	32	44		MHz	I_f = 20 mA dc

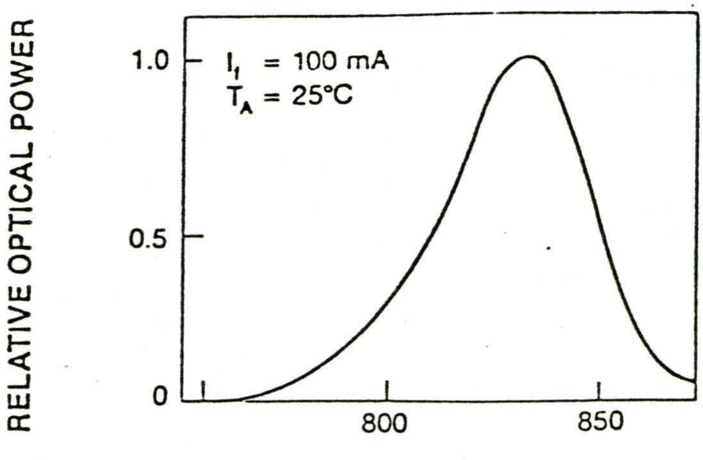


Fig 8 Relative spectral output

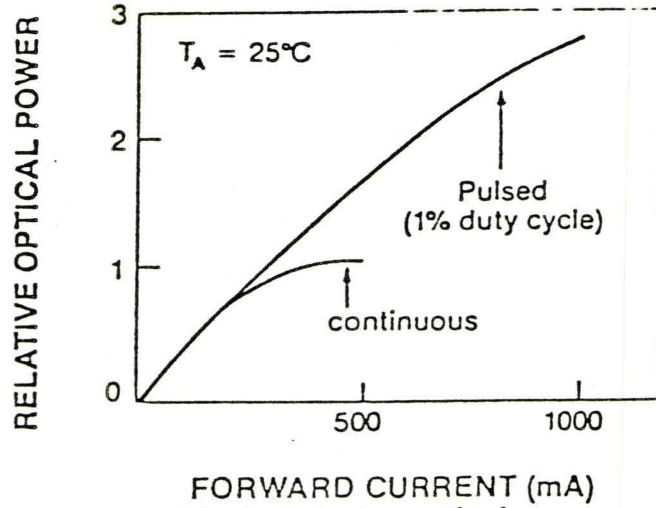


Fig. 9 Relative optical power output vs forward current

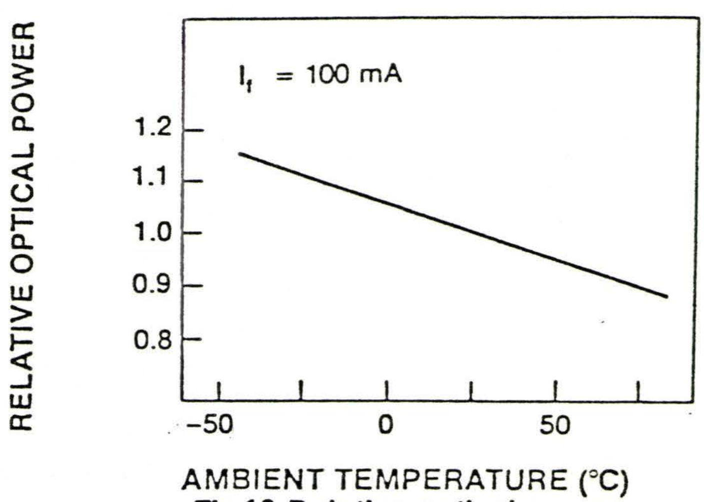


Fig 10 Relative optical power output vs ambient temperature

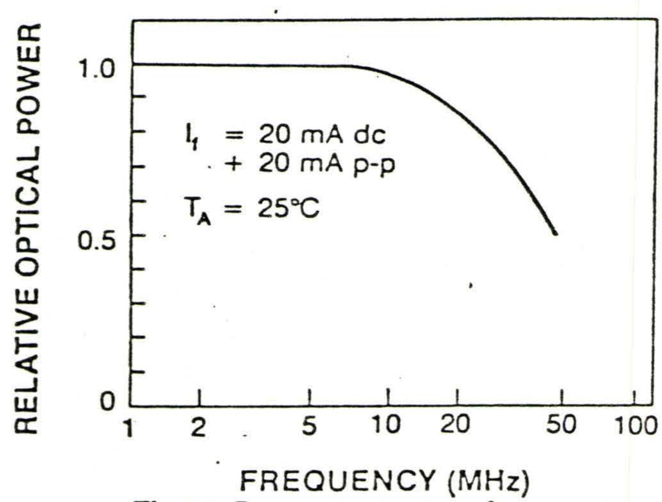


Fig.11 Power output vs frequency

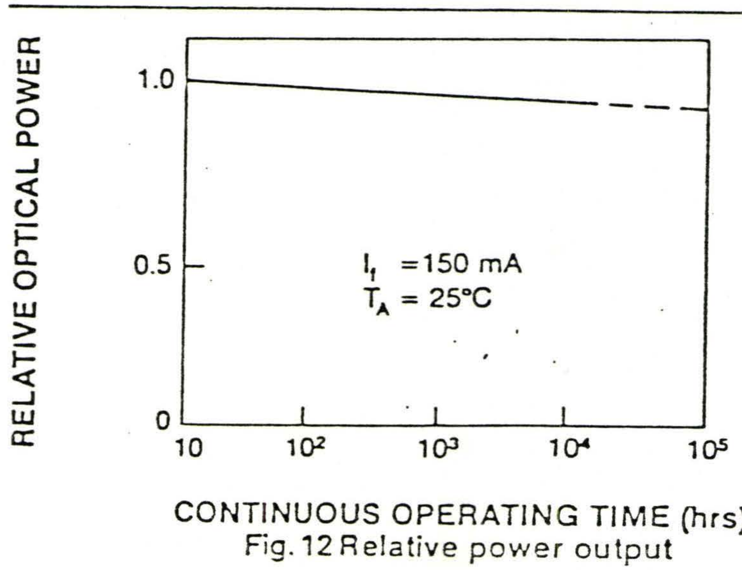


Fig. 12 Relative power output

Figure 13

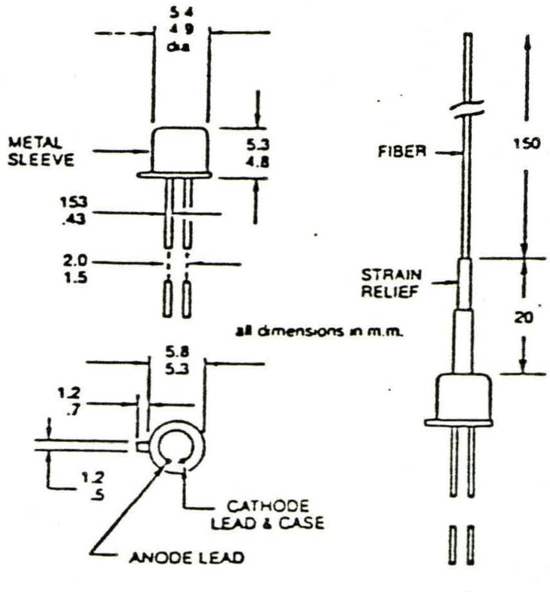


Figure 14

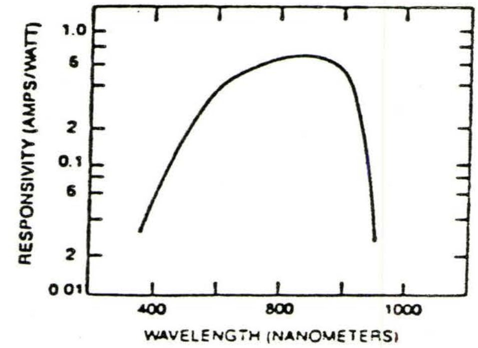


Figure 15

MAXIMUM RATINGS	
DC reverse operating voltage	45 V
Average photocurrent-continuous	0.5 mA
Peak photocurrent	5 mA
Average forward current-continuous	5 mA
Peak forward current	50 mA
Operating and storage temperature (NT D-5-1)	−40 to +80°C

Figure 16

PHOTODIODE CHARACTERISTICS (T_A = 25°C)	Min	Typ	Max	Unit	Test Condition
Breakdown voltage	100			V	
Responsivity	0.5	0.55		A/W	λ = 840 nm
Quantum efficiency	75	85		%	λ = 840 nm
Dark current		1	10	nA	V_R = 20 V
Capacitance (chip + package)		0.6	0.8	pF	$V_R \geq$ 15 V
Rise and fall time (10-90%)		3	4	ns	R_L = 50 Ω
					λ = 840 nm V_R = 45 V

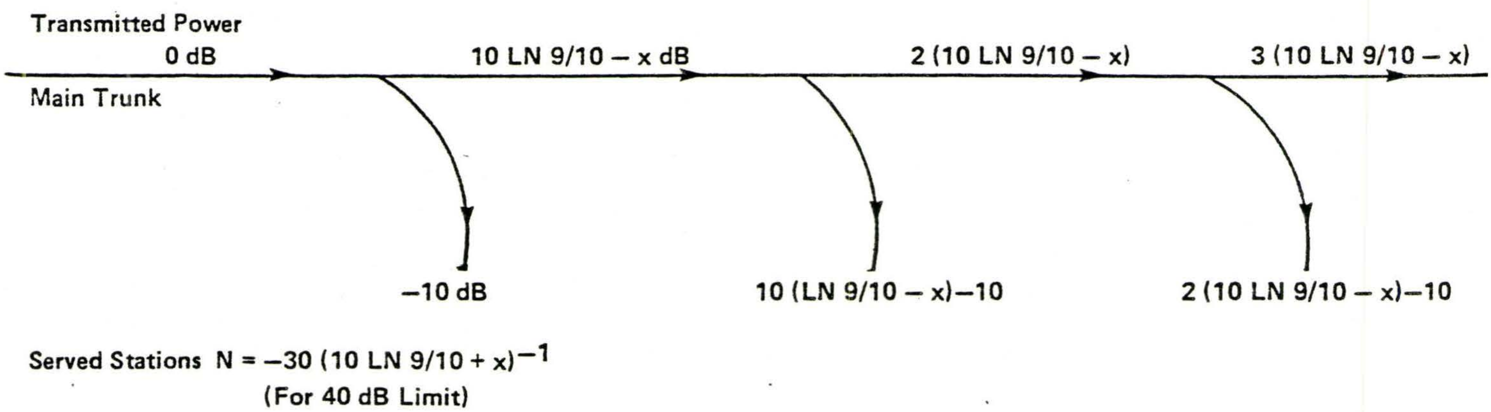


Figure 17 Tree System

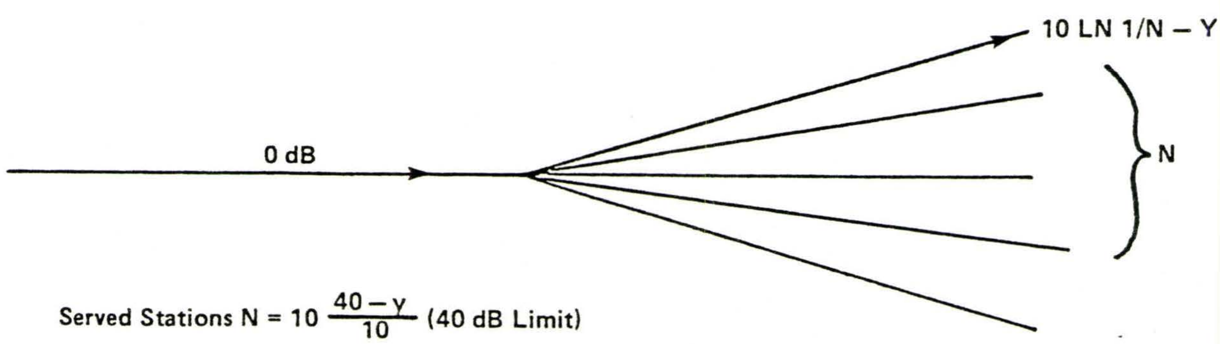


Figure 18 Star System

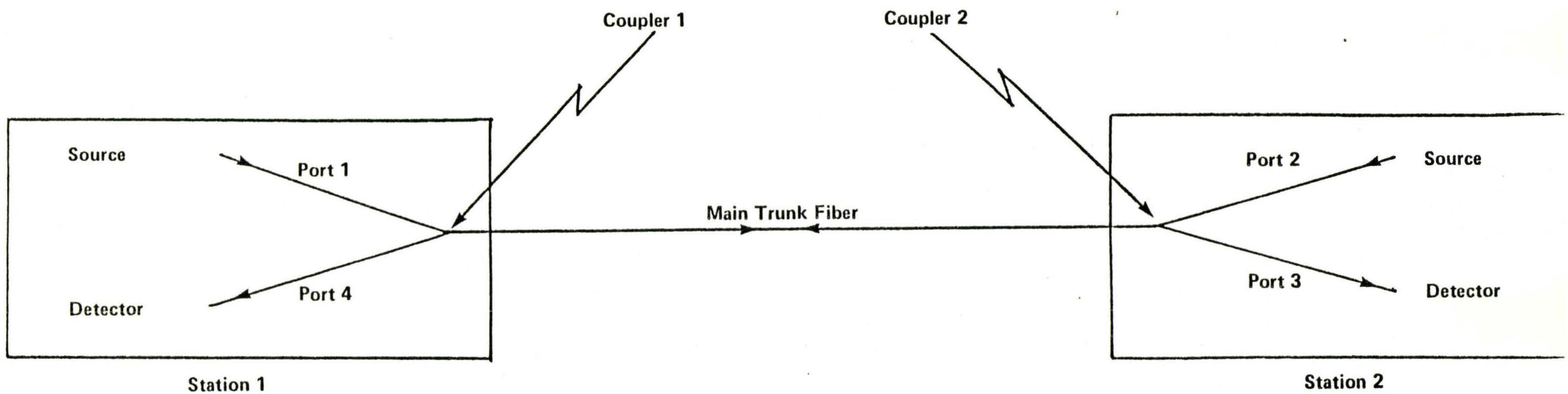


Figure 19 Bi–Directional Transmission

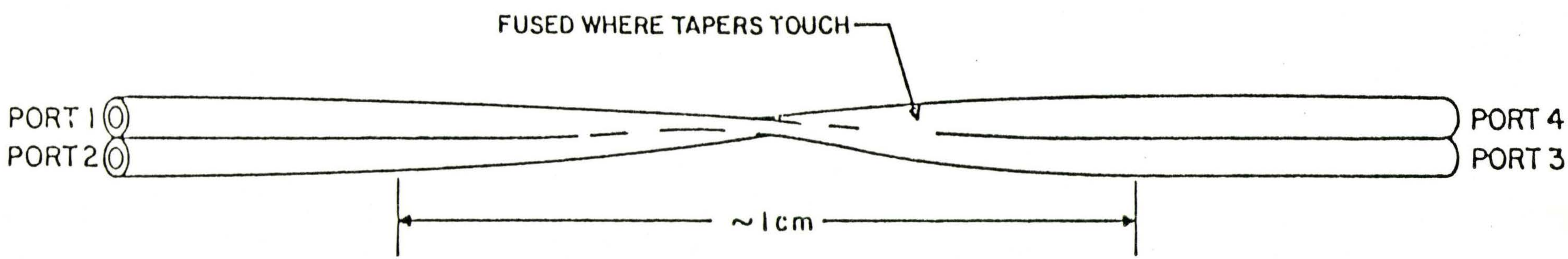


Figure 20 Biconical Taper Coupler

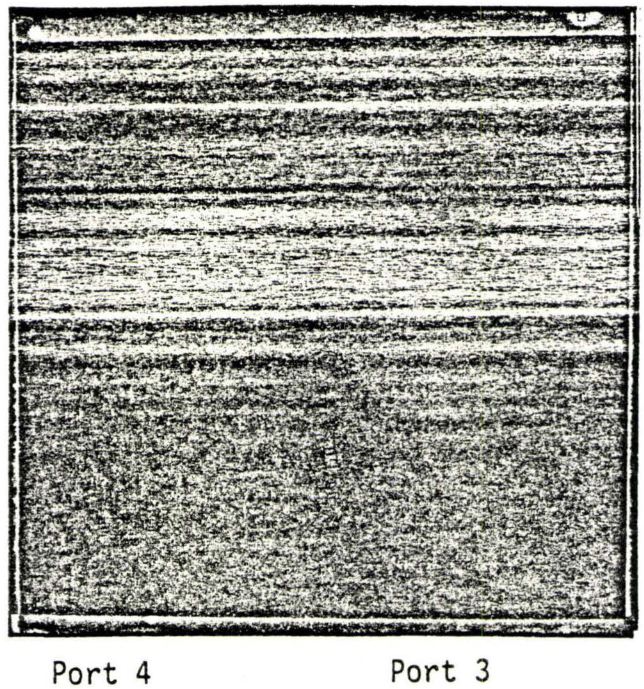


Figure 21 : Far Field Pattern from Bidirectional Coupler

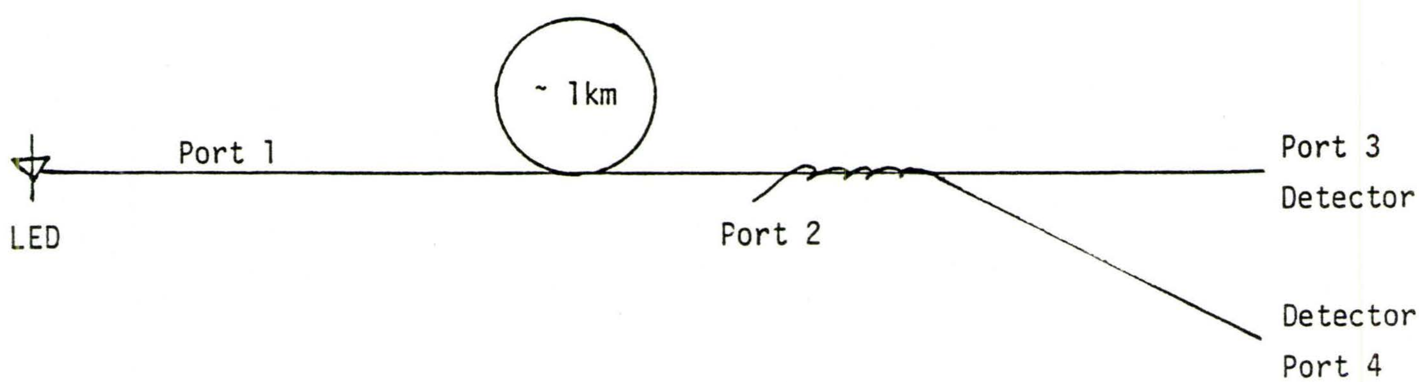


Figure 22 : Loss Measurement

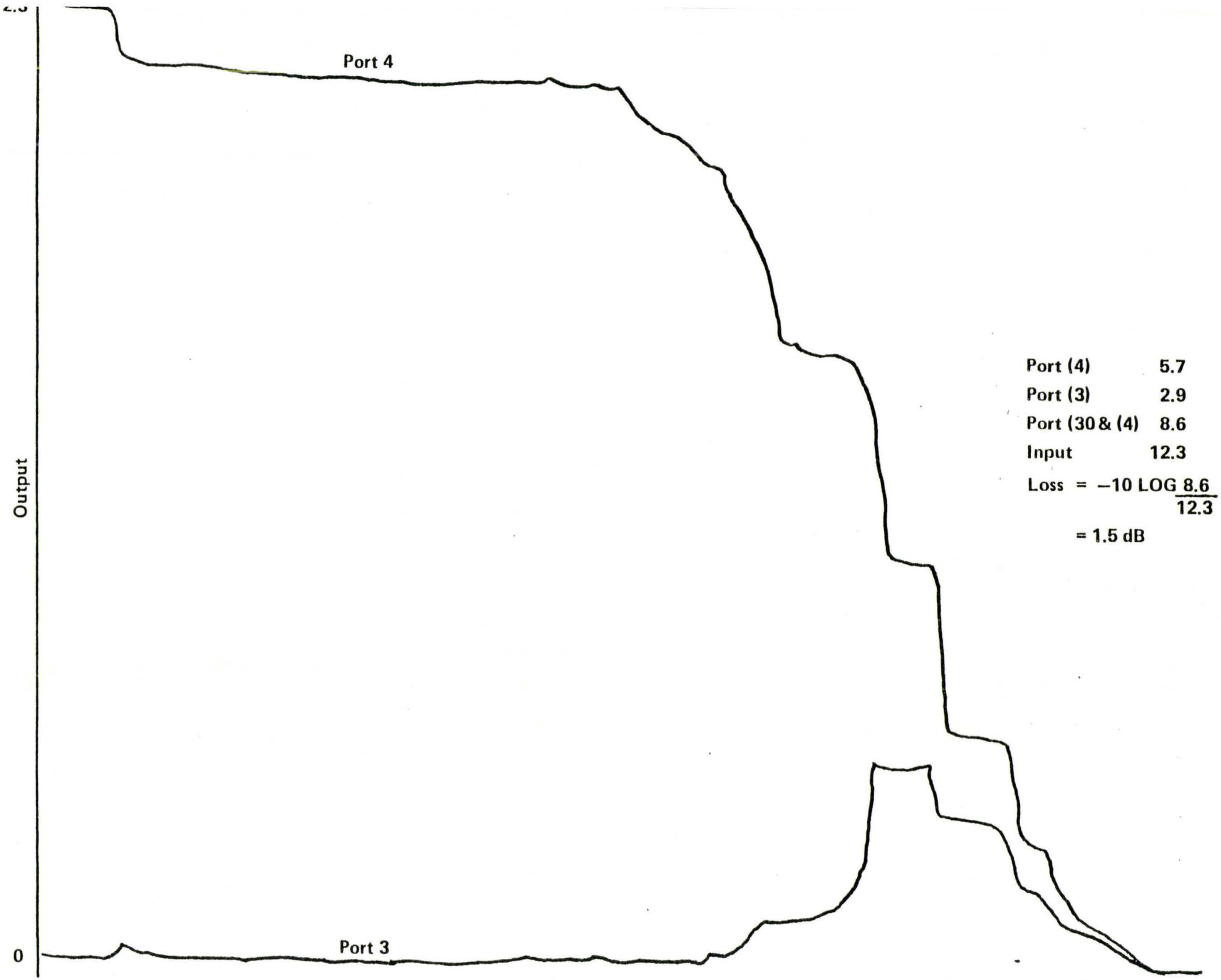


Figure 23 : Coupling Ratio Graph

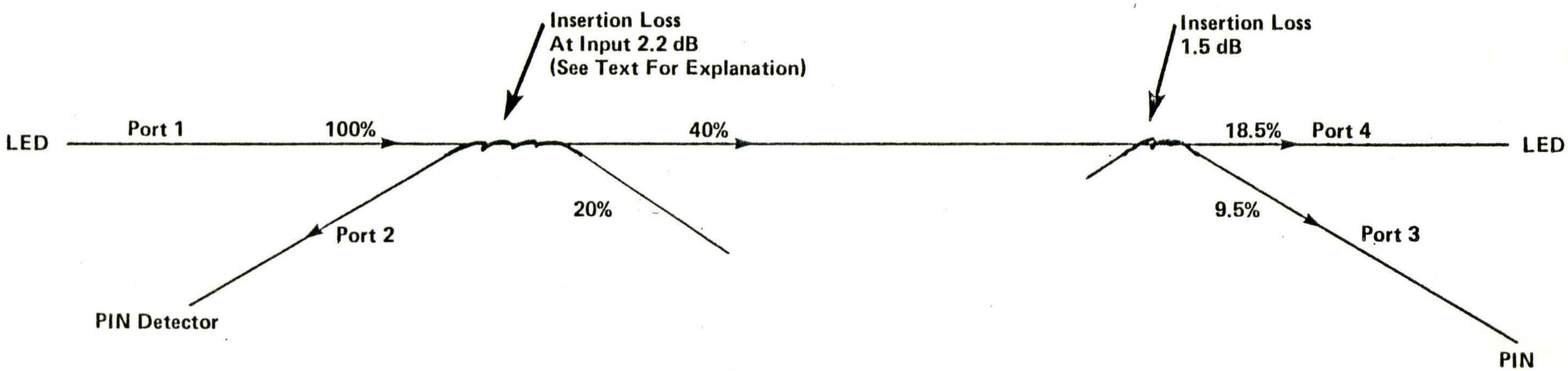
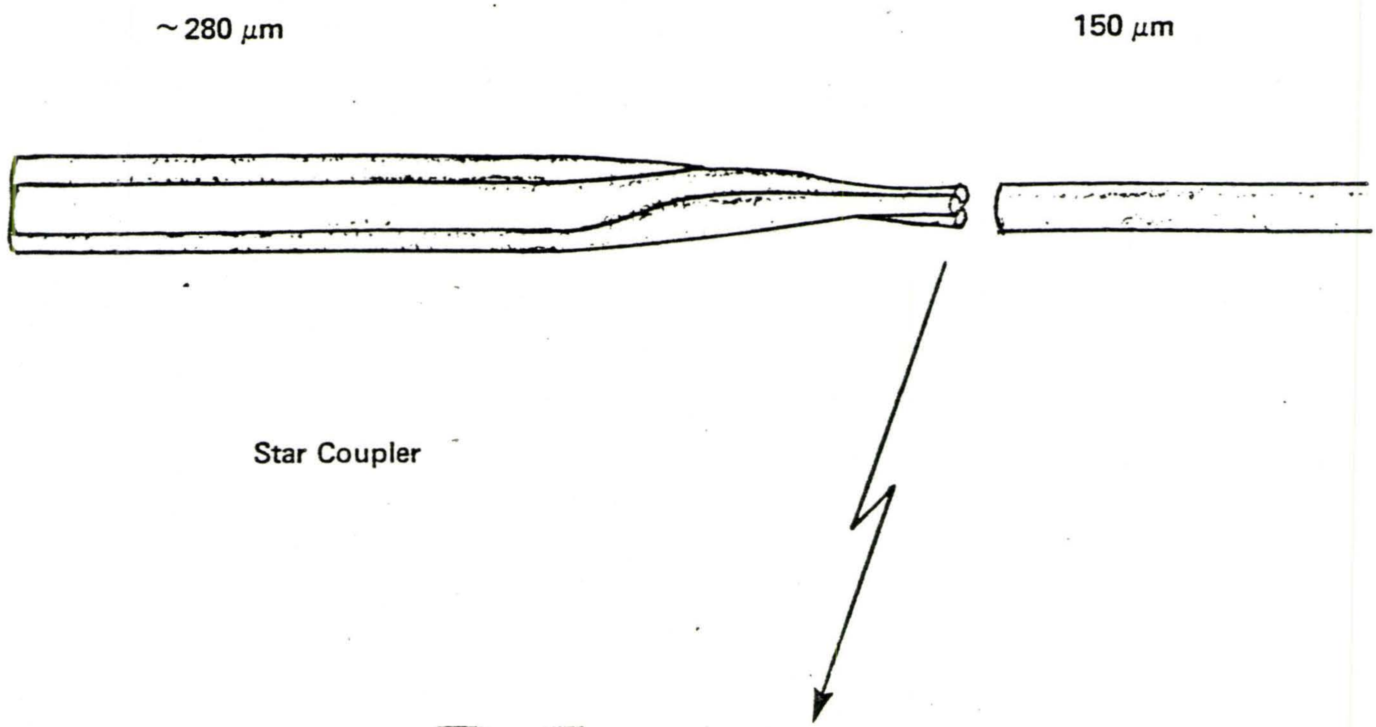


Figure 24

Bidirectional Loss Layout

Figure 25



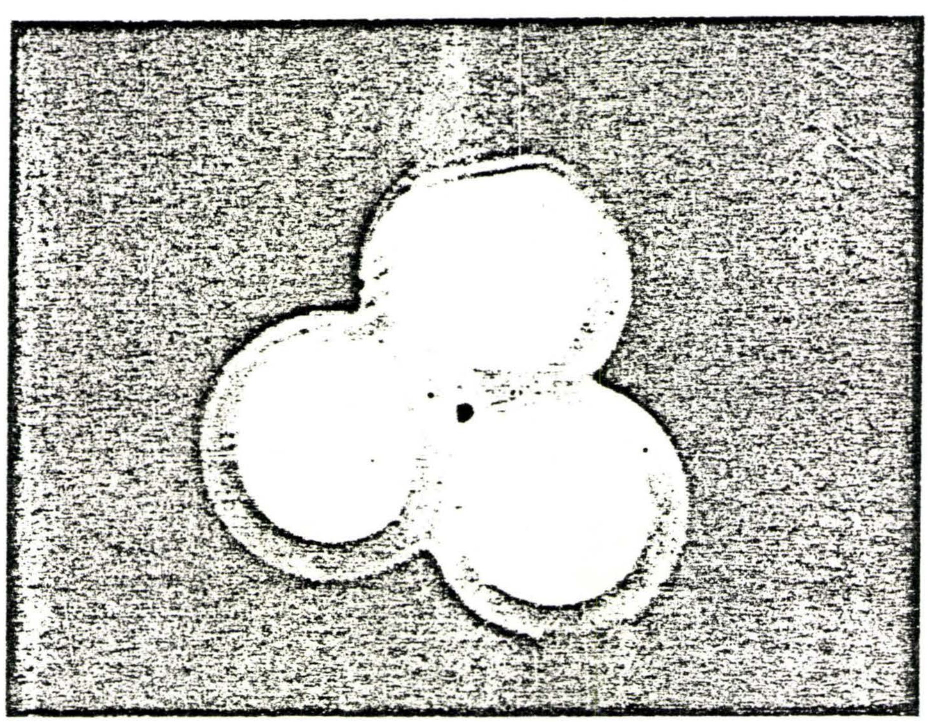


Figure 26 Cleaved Endface of 3 Fused Fibers

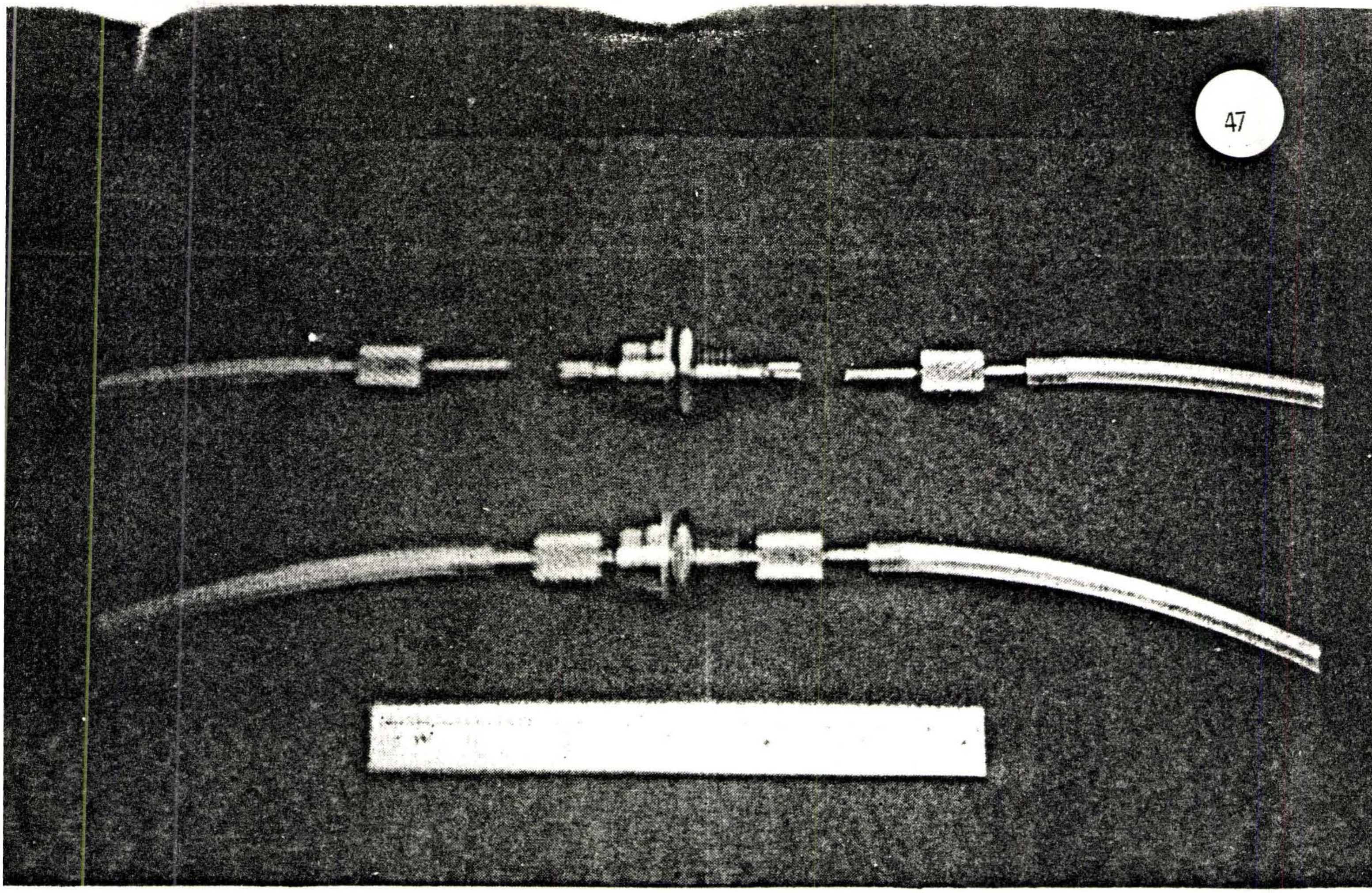


FIG. 27 OPTICAL FIBRE CONNECTOR

INSERTION LOSS
1.0 dB

DATA	
Dimensions:	4.5 cm (1.75") long by 1.0 cm (0.375") diameter
Fiber Cladding Diameter(1)	100 μm to 175 μm (0.004" to 0.007")
Coated Fiber Diameter(2)	up to 0.75 mm (0.03")

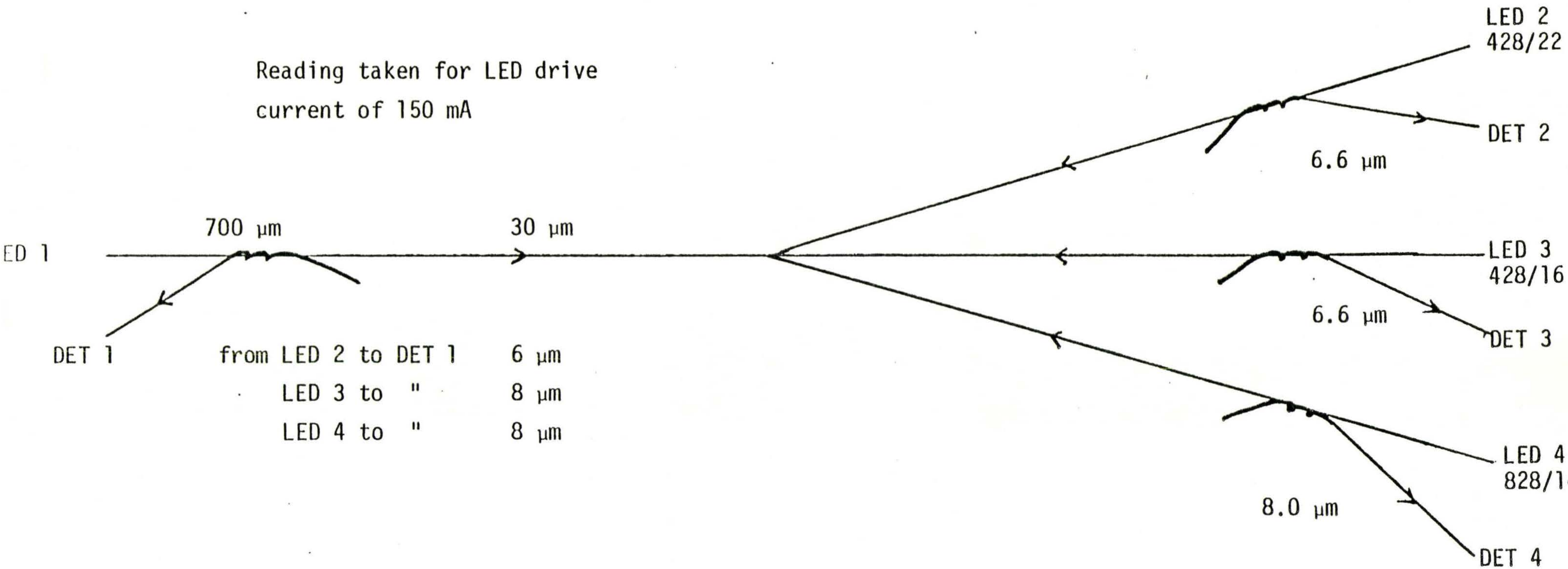


Figure 28(a) : System Layout Results Before Connectorizing

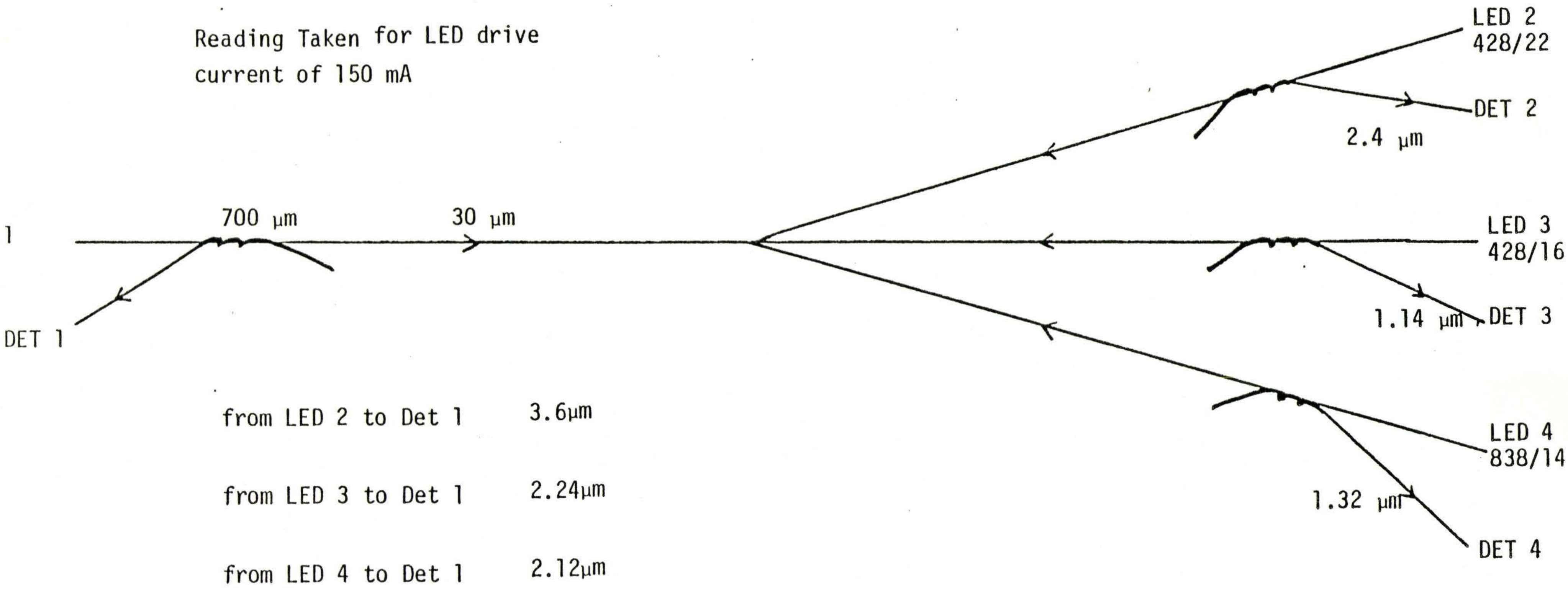


Figure 28(b) : System Layout Results After Connectorizing

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