Technical Report

A Systems Study of Fiber Optics for Broadband Communications

Activity No. 1
State-of-the-Art Review
of Fiber Optic Technology

BNR Project TR 6259
November 1976
Revised April 1977

Bell-Northern Research

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for
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under DSS Contract
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STATE-OF-THE-ART REVIEW OF FIBER OPTIC TECHNOLOGY

by

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TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd)

TABLE OF CONTENTS (cont'd)

TABLE OF CONTENTS (cont'd)

TABLES

TABLE OF CONTENTS (cont'd)

FIGURES

TABLE OF CONTENTS (cont'd)

1. INTRODUCTION

by K.Y. Chang

A systems enginering study on the use of optical fibers for switched and non-switched broadband communications is presently being carried out by BNR. This study will define suitable system concepts and network topologies using fiber optics to provide broadband communications, such as CATV, interactive video, and integrated video, data and voice. Special attention will be given to the needs of rural areas. Further, the technical, operational and economic feasibilities of such broadband systems are to be investigated. Before efforts are devoted to studies in these areas, however, it is imperative that the capabilities and limitations of current fiber-optic devices, components and subsystems be well understood. This state-of-the-art review report is prepared to serve this end.

The review in this report is separated into ten sections. First, in Sections 2, 3 and 4, the three basic components of fiber-optic communication systems, namely light source, photo-detector and optical fiber, are covered. Section 5 discusses the properties of optical fiber cables. Section 6 reviews the splices and connectors for optical fibers and optical fiber cables. This is followed by a review of fiber-optic directional couplers in Sections 7 and 8. Section 9 deals with electro-optic transmitters, receivers and repeaters, for both analogue and digital applications. Fault locating techniques for fiber-optic cables and repeaters, which are still at early development stages, are briefly reviewed in Section 10. Finally, in Section 11, experimental and field trial systems reported to date are discussed.

Two sections are devoted to the review of the directional coupler, which may be an essential component in a broadband communication system, particularly in the distribution environment. These two sections were prepared independently by two different individuals and from two different viewpoints, i.e. systems (Section 7) and device principles (Section 8). Although there is a certain degree of duplication, it is deemed that the differences warrant the inclusion of both in this report.

Wherever possible, we have also discussed in each section the availability of the component or subsystem in question, both at the commercial off-the-shelf level and at the product development level. Also, where appropriate, tables are provided to compare the characteristics of components and subsystems of various firms and laboratories.

Since each section was prepared separately by different individual(s), there may exist non-uniformity in format or duplications in contents. It is hoped that the reader will bear with us for the inconveniences that are encountered.

2. LIGHT SOURCES

J.C. Dyment F.P. Kapron F.D. King

2.1 INTRODUCTION

Light sources to be used in transmitters for fiber optical systems are generally of the solid state injection diode type. Diode sources have the advantages of compactness (less than a mm square); low electrical power dissipation ($<$ 1W) and ease of modulation. The materials from which the devices are made depend upon the emission wavelength range desired. Most effort has been in the GaAs-GaAlAs system with peak wavelengths ranging from 800 to 950 nm. Shorter wavelength visible radiation attainable with GaAs-GaAsP materials is not suitable because of the higher fiber attenuation[1]. On the other hand, sources of light in the 1.0-1.3 um range are desirable from the point of view of lower attenuation[1] and lower chromatic dispersion[2], but work with suitable GaAsSb[3] and GaInAsP[4] materials is only in the laboratory stage. Lead salt diodes[5] operating beyond 4 um are not of interest for fiber transmission. The discussion of specifications below will therefore be restricted to GaAs-GaAlAs[6] devices as these are being used in prototype systems and many are available commercially. Diode sources are classed into two broad categories; incoherent "light-emitting diodes" (LED's) and partially coherent "laser diodes".

2.2 SOURCE PARAMETERS

Several properties common to the characterization of both LED's and laser diodes are now defined.

Radiant flux P_o: optical power leaving the device, totally or out acet (unit: watts, W).

(External quantum efficiency) $\eta = P_o/P_e$: radiant flux divided by t the input electrical power P (expressed as %).

Differential (external quantum) efficiency $\eta = dP_o/dP_e$: rate of change of the radiant flux with respect to electrical power (expressed as %)

Radiant intensity $dP_o/d\Omega$: radiant flux per unit solid angle in the direction considered (unit: watt per steradian, W/sr)

Radiance (brightness) $B = d\,P\,/d\Omega dA \cos\theta$: radiant flux per unit solid angle (radiant intensity) and per unit emitting area A normal to the direction considered; θ is the angle between the normal to the emitting element dA and the direction (unit: watts per steradian and per square meter, W/sr-m^2).

Beamwidth $\Delta\theta$: the angle between the directions for which the radiant intensity is half (unless otherwise stated) of its peak value (unit: degrees° or radians r). For most diodes, the beamwidth in the plane parallel to the emitting plane ($\theta_{\parallel}$) is different from the beamwidth perpendicular to the emitting plane ($\theta_{\perp}$).7

Lambertian source: one for which the radiance distribution is uniform in all directions θ and over all of the emitting area A. The 50% beamwidth $\Delta\theta$ is 60°.

The radiance distribution has a profound effect on source-to-fiber coupling efficiency and it is desireable to have beamwidths corresponding to the full acceptance angle θ_c of the fiber, measured in air, which is typically 15° to 30°. Even with collimating optics, a Lambertian source is limited to a coupling efficiency, C.E., given by:

$$C.E. = \frac{A_f}{A} \frac{\sin^2(\theta_c/2)}{n^2}$$

where: A_f is the fibre core area, A is the source area ($A \lessgtr A_f$), and n is the refractive index of the source material. (8).

When graded index fiber is used this factor is reduced by a further factor:

$$1 - A/2A_f \qquad (9).$$

A more directional radiant intensity, as in lasers, may often be of the form $(\cos\theta)^m$, $m > 1$. (m = 1 for Lambertian) resulting in better coupling.

Peak wavelength λ_p: wavelength at which the source spectrum has its maximum value of radiant flux (unit: nm). This wavelength is important in determining the fiber's attenuation and specific chromatic dispersion D (note D(λ_p= 800 nm) = 0.1 ns/km-nm, D(950 nm) = 0.05 ns/km-nm)10 for silica-core fibers.

Spectral bandwidth $\Delta\lambda$: the difference between the wavelengths for which the radiant flux is half (unless otherwise stated) of its peak value at (unit: nm). The bandwidth is important in determining the absolute chromatic dispersion $D \cdot \Delta\lambda$ (ns/km).

Current density J = I/A: electrical current I to the device divided by the active area A. (units: amperes per square centimeter, A/cm^2).

Threshold current I : minimum electrical current for which lasing is detectable (over the spontaneous emission).

Risetime t : the time between the 10% and 90% levels of the optical power response to a step input rectangular electrical pulse. For a laser diode, this value is detector limited to < 0.1 ns; a more significant parameter for laser diodes would be the delay time between the application of a current pulse and the onset of stimulated emission.[11] The time delays range from a few nanoseconds at zero dc bias to 0.1 nsec at dc bias levels just below I_{th}[12] . To achieve the maximum modulation rates, lasers must be operated in this latter mode.

Device lifetime T: for an LED operated at a constant current and temperature, the time for the output optical power to decay to half its initial value; for a laser, there is no universally accepted definition of device lifetime. Typically, the laser is operated at $I \approx 1.3\ I_{th}$ via periodic manual resetting[13] or feedback[14] control of the current. The device lifetime is then the time over which lasing occurs.

Linearity: of output optical power vs. input electrical current; it is expressed as the dB ratio of harmonic optical power (second and higher) to fundamental optical power when a sinusoidal electrical signal is applied[15]. Additional details are given in the section on "Linearity of Light Sources".

Laser stability : the ability of the laser to maintain a linear relationship between P and I when above threshold. Mode structure instabilities cause "kinks" in this characteristic which generally decrease in frequency as the width of the lasing active region is decreased[16].

2.3 DIODE LASER LIGHT SOURCES

Table 2.1 lists only diode lasers capable of CW operation at room temperature which have a "stripe geometry" configuration[17]. Pulsed laser diodes have been omitted (since these are a sub-class of the CW diodes) along with laser arrays (since these are intended for high pulsed power applications and do not possess the mode control desired for optical communication systems). The first four entries in the table are commercially available while the remaining seven were selected to illustrate the current status of laboratory development. Many of these lasers (BTL, NEC, Hitachi, Fujitusu) are currently undergoing field trials in fiber optic communication systems.

2.4 LED LIGHT SOURCES

Table 2.2 shows the structure and characteristics of the principal LED structures which are suitable for single-fiber-channel optical communication systems and are currently being developed or are commercially available. Devices suitable for use with optical fiber bundle systems are offered by several manufacturers (Spectronics, Texas Instruments etc.).

Linearity characteristics[15] of the various LED's are not included in the table since, with the exception of structure (I), these have not been reported.

2.5 LINEARITY OF LIGHT SOURCES

2.5.1 Introduction

To characterize light sources with respect to linearity the total harmonic distortion figure (THD) is used as figure of merit.

The THD figure is defined as:

$$THD = 20 \log \left| \frac{\sqrt{\sum_{n=1}^{m} V^2 \quad (nw)}}{V(w)} \right|$$

where V(w) denotes the amplitude of the signal (electrical) detected at the fundamental modulation frequency w and V (nw), n = 1,2..m, denotes the amplitude of the nth harmonic component of the fundamental.

To describe the relative level of the nth harmonic component we define nth order harmonic distortion, γ_n (nw) as:

$$\gamma_n \; (nw) = 20 \log \left| \frac{V(nw)}{V(w)} \right|$$

Distortion characterization can also be performed with respect to multiple test signal inputs (29). For two signal modulation tests the 2nd and 3rd order harmonic distortion figures $\gamma 2$ and $\gamma 3$ respectively, (also known as 2nd and 3rd order intermodulation figures) are defined as:

$$\gamma_2 \quad (w_1 \pm w_2) = 20 \log \left| \frac{V(w_1 \pm w_2)}{V(w)} \right|$$

$$\gamma_3 \; (2w_{1,2} \pm w_{2,1}) = 20 \log \left| \frac{V(2w_{1,2} \pm w_{2,1}}{V(w)} \right|$$

where

$$V(w) = V(w_1) - V(w_2)$$

For three signal modulation tests, the 3rd order distortion (3rd order intermodulation) figure can also be defined as:

$$k_3 \; (w_1 \pm w_2 \pm w_3) = 20 \log \left| \frac{V(w_1 \pm w_2 \pm w_3)}{V(w)} \right|$$

and

$$V(w) = V(w_1) = V(w_2) = V(w_3)$$

Provided the distortion is independent of modulation frequency and provided the distortion characteristics are obtained within the bandwidth of the device under test, the following relationships are valid between γ_2, γ_3 and k_3 and Δ_2 and Δ_3 respectively.

$$\Delta_2(2w) = \gamma_2(w_1 \pm w_2) - 6 \text{ dB}$$

$$\Delta_3(3w) = \gamma_3(2w_{1,2} \pm w_{2,1}) - 9.5 \text{ dB}$$

$$\Delta_3(3w) = k_3(w_1 \pm w_2 \pm w_3) - 15.6 \text{ dB}$$

2.5.2 LED Linearity

Distortion measurements performed on Burrus type double heterostructure LED's have shown [30,31] that the linearity of LED's is only weakly dependent on device doping.

A typical set of total harmonic distortion (THD) curves as a function of dc bias obtained at four different modulation levels is shown in Fig. 2.3. The distortion measurements were performed at a fundamental frequency (w) of 1 kHz. At 100 mA dc, 100 mA p-p modulation currents the THD figure of this type of device is in the vicinity of -33 to -35 dB down on the fundamental. No significant changes in distortion were observed for modulation frequencies increasing up to 5 MHz. At higher frequencies the linearity improves 2-3 dB's as the bias current increases. When the modulation index is smaller than 0.75, the dominant source of nonlinearity is due to second harmonic (2w) generation. The level of third harmonic (3w) is 15-25 dB below the second (Fig. 2.4).

The dependence of the THD on ambient temperature from -65°C to 120°C has also been investigated [30]. In general, results of measurements show that with decreasing temperatures the linearity of LED's improves (Fig. 2.5) At 100 mA dc bias, 100 mA p-p modulation currents distortion in LED's increases linearly by about 0.06 dB/°C.

Multisignal distortion measurements on Burrus LED's have also been performed [32]. With test signals at respectively 5,6 and 12 MHz, modulation amplitudes of 50 mA p-p and dc bias of 90 mA, the 2nd and 3rd order distortion figures γ_2 and k_3 were in the vicinity of respectively -40 dB and -75 dB down on the fundamental. These figures are approximately -6 dB and -8 dB lower than expected on the basis of single tone measurements.

2.5.3 Laser Linearity

To date, the only known result of distortion measurements on lasers has been given by O'Brien , quoting -40 dB 2nd harmonic distortion at 30 mA p-p, 10 MHz modulation current.

Preliminary distortion measurements in BNR have also shown that with optical power output of .240 mW rms, (10 mA p-p modulation, laser external slope efficiency 0.34 mW/mA) THD figures as low as -40 dB are attainable (fig. 2.6).

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TABLE 2.1 LASER DIODES FOR CW OPERATION AT ROOM TEMPERATURE

	COMPANY	STRUCTURE (see Figure)	EMITTING AREA $(\mu m)^2$	P_o (mW)	I_{th} (mA)	$\Delta\theta_{\parallel} \times \Delta\theta_{\perp}$ (degrees)	λ_p (nm)	$\Delta\lambda$ (nm)	STABILITY	T, DEVICE LIFETIME (hr)	COMMENTS
COMMERCIALLY AVAILABLE	RCA	I	13x2	5-10 ($\eta_d \sim 3\%$, one end)	250	10x40	820	3	Fair	No claim	Commercial #C30127, C30130; hermetically sealed with passivated mirrors. Need lens to couple to fiber. (10^4 hrs lifetime in lab.)
COMMERCIALLY AVAILABLE	LDL (Laser Diode Labs)	IV	13x0.3	7-14	200	5x55	850	3	Fair	No claim	Commercial #LCW-5, LCW-10. Need lens to couple to fiber.
COMMERCIALLY AVAILABLE	NEC	III	15x0.3	5 ($\eta_d \sim 3.5\%$, one end)	120	10x40	830	3	Fair	Guaranteed 1000 hrs	Commercial #V387 supplied with Selfoc fiber attached and current feedback to maintain fixed P_o. Built-in circuit determines laser "on" time.
COMMERCIALLY AVAILABLE	ITT	I	15x0.3	5-10	$\sim$200	Note (1)	840	3	Good (claimed)	3%/1000 hrs reduction in P_o claimed	Lab models ($>10^4$ hrs lifetime) No passivation on mirrors.
LABORATORY	BTL	II	13x0.2 8x0.2	$\sim$5 $\sim$3	$\sim$100 $\sim$100	Note (1)	840	3	Fair Good	$>3 \times 10^4$	- Projected room temperature lifetime $>10^5$ hrs - Narrow stripes show good stability up to 3.5mW output per mirror

(continued)

TABLE 2.1(Cont'd)

LABORATORY MODELS

COMPANY	Structure (see Figure)	EMITTING AREA $(\mu m)^2$	P_o (mW)	I_{th} (mA)	$\Delta\theta_{\parallel} \times \Delta\theta_{\perp}$ (degrees)	λ_p (nm)	$\Delta\lambda$ (nm)	STABILITY	T, DEVICE LIFETIME (hr)	COMMENTS
HITACHI	V	15x0.5	∿5	∿50-100	10x40	830-880	3	Fair	>3000	-Commercial availability expected in near future -60-70% of P_o coupled to fiber using another fiber as lens; 20-40% without fiber lens
FUJITSU	VI	10x0.2	?	70-100	Note (1)	810	3	Good	>3000	-Stable modes up to $3I_{th}$. I_{th} increases more slowly as active width reduced than structure II.
HP	II	10x0.3	?	∿100	Note (1)	840	3	Fair to Good	$>10^4$	-This laser will be used in new surveying instrument by HP
HITACHI	VII	50x0.2	10@1.3I_{th}	∿1300	Note (1)	890	<0.02	Good	few hours	-Mode stability and narrow $\Delta\lambda$ are outstanding features. Long lifetime may be difficult to obtain.
HITACHI	VIII	∿1 to 5 x 0.3 to 0.5	∿0.5	15-50	$\binom{30}{40}$x40	820	2	Good	$\lesssim 3000$	-No "kinks" in P_o vs I -Nearly circular output beam possible -Low output power; lifetime poorer than others
MITSUSBISHI	IX	∿1 to 2 x 0.3	∿0.5	40	Note (1)	-	-	Good	$>10^4$	-Good stability as for structure VIII but improved lifetime.

Note (1) - Data unavailable but for stripe widths of 13-15 μm, one can expect $\Delta\theta_{\parallel}$ to be about 10^o. As the stripe narrows, $\Delta\theta_{\parallel}$ will increase and have an expected value of $20\text{-}30^o$ for structure IX. For all structures $\Delta\theta_{\perp}$ would be about 40^o.

TABLE 2.2

Characteristics of High Radiance LED's for Single Fiber Channel Optical Communications

COMPANY	STRUCTURE (see Fig.)	EMITTING AREA GEOMETRY	B AT $3kA/cm^2$ ($W/sr\text{-}cm^2$)	MAXIMUM[1] ALLOWED DC CURRENT DENSITY (kA/cm^2) SPECIFIED	t_r (ns)	λ_p (nm)	$\Delta\lambda$ (nm)	ESTIMATED[2] OR REPORTED POWER AT 200 mA DRIVE (μW)	COMMENTS
BNR	I	90 μm Diameter Dot	22 44 66	6 6 6	4 7 14	840	40 45 45	130 270 400 ($4\ kA/cm^2$) Flat Butt	BNR -10,15,30-2, 3 Supplied with or without fibers attached
PLESSEY	II	50 μm Diameter Dot	12	10	7	900	24-38	70 ($10\ kA/cm^2$) Flat Butt	PLESSEY HR 954
RCA	III	65x0.1 μm^2	560	10	1.5	840	34	220 Ball Ended Fiber ($2.6kA/cm^2$)	Devices having 1/10 output are commercially available
HITACHI	IV			250 mA Total	8	750-890	30	200 domed LED	Emitting area unknown
FUJITSU	V	35 μm Diameter Dot		10	17 6	810	20	600 ($10kA/cm^2$) Ball Ended Fiber	

(1) All devices listed are claimed to have lifetimes in excess of 10^5 hours under specified operating conditions

(2) Fiber NA = 0.16, core diameter 85 μm, step index

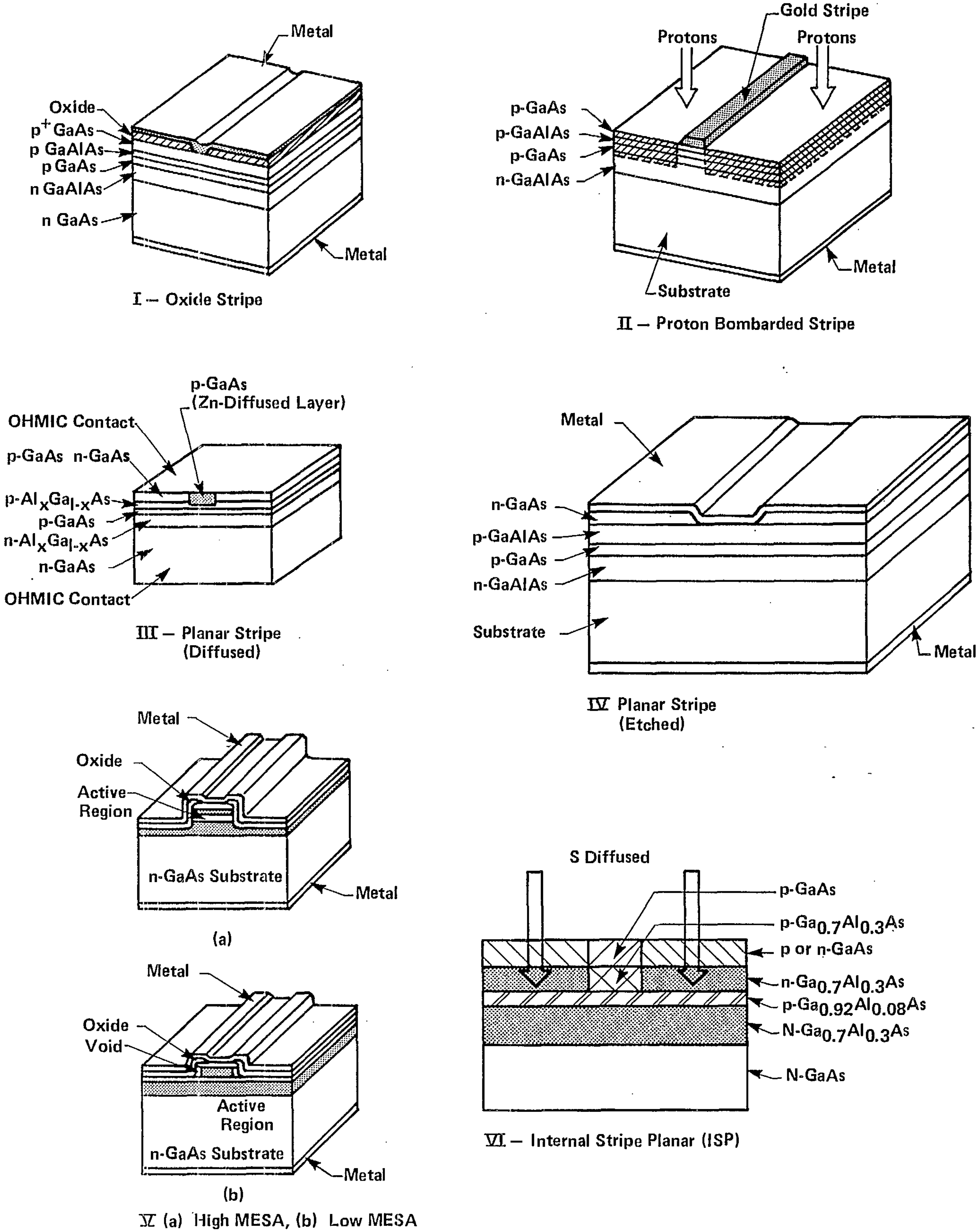
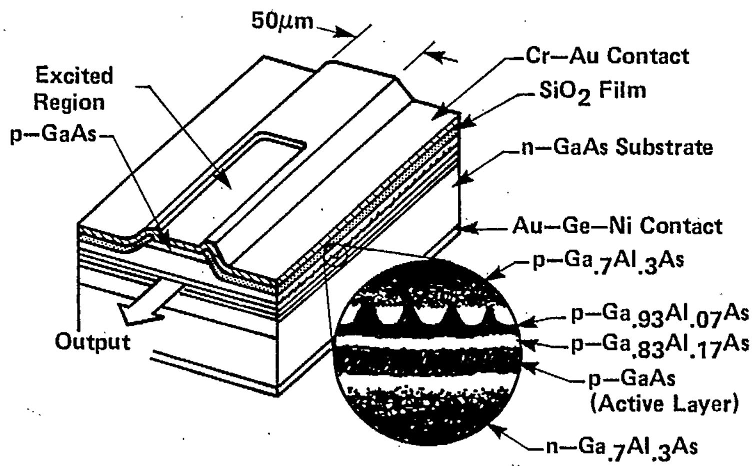
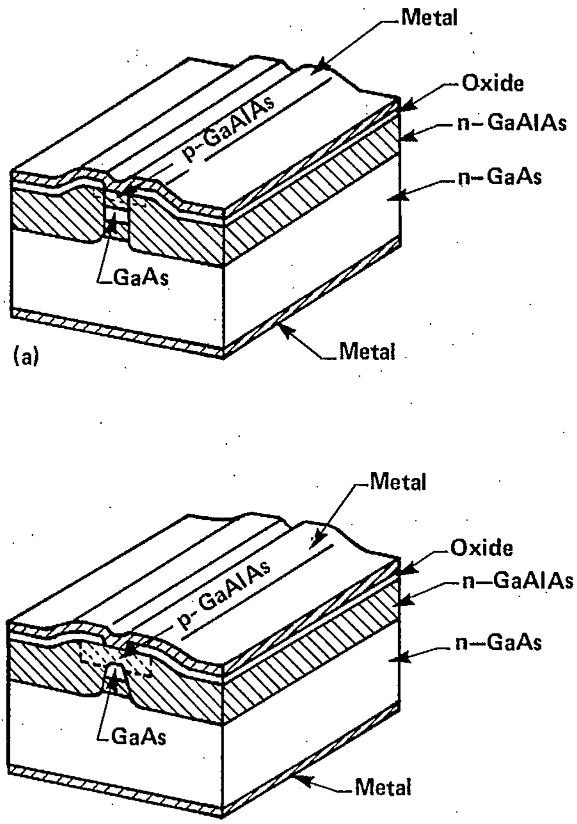


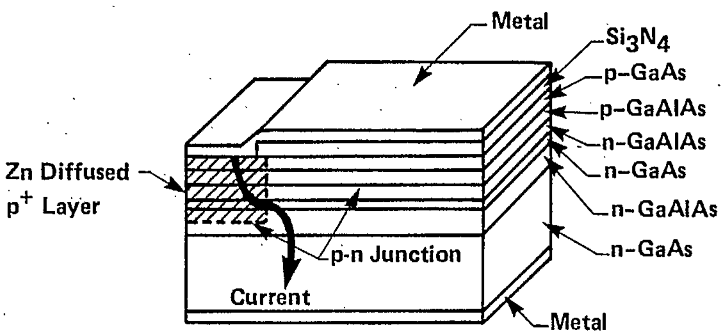
Figure 2.1 Stripe Geometry Configurations for Laser Diodes



VII – Striped Distributed Feed-Back (DFB) Laser

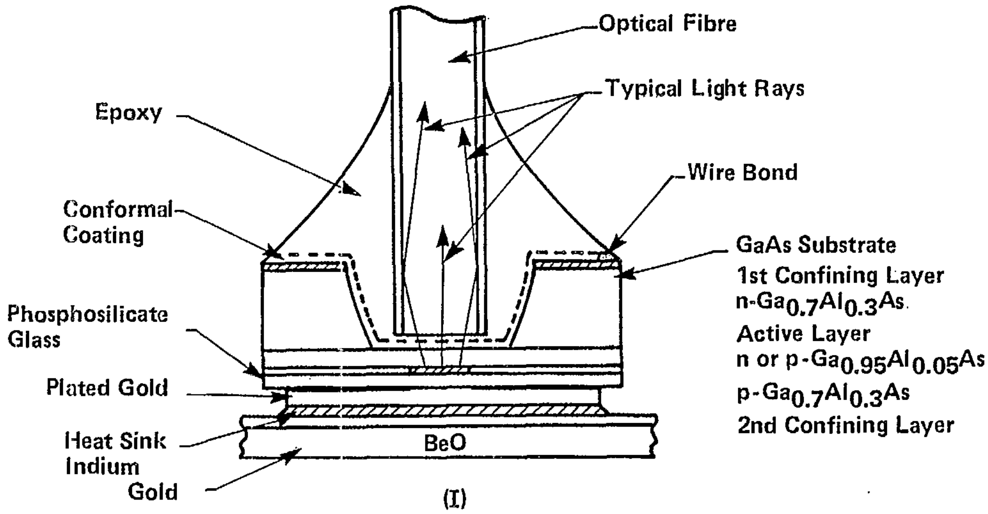


VIII – Buried Layer Heterostructure (Striped)

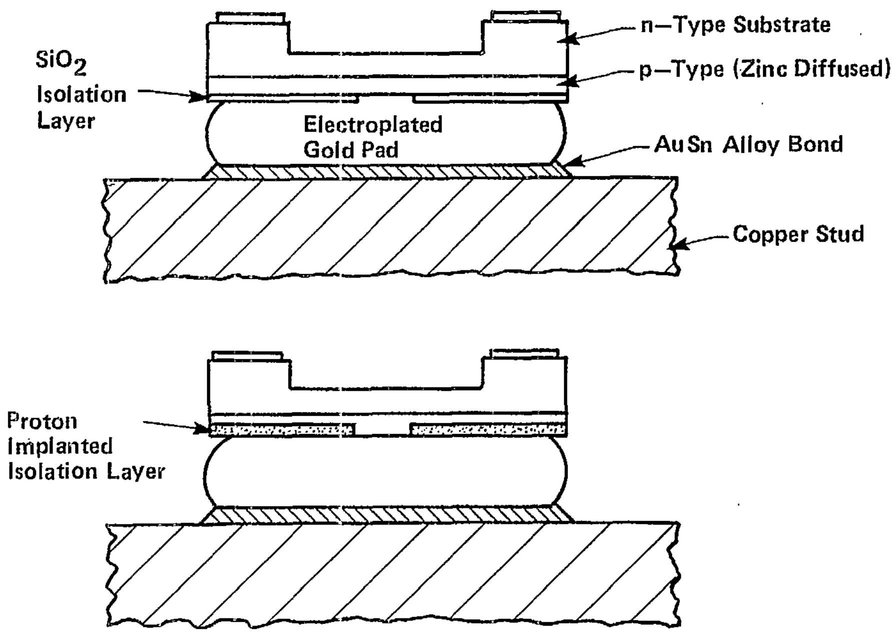


IX – Transverse Injection Laser

Figure 2.1 Stripe Geometry Configurations (Cont'd) for Laser Diodes

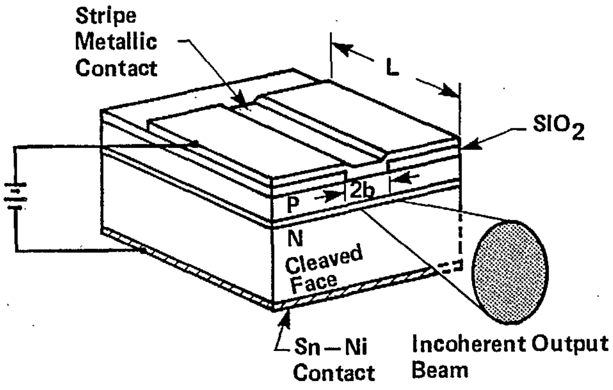


(I)

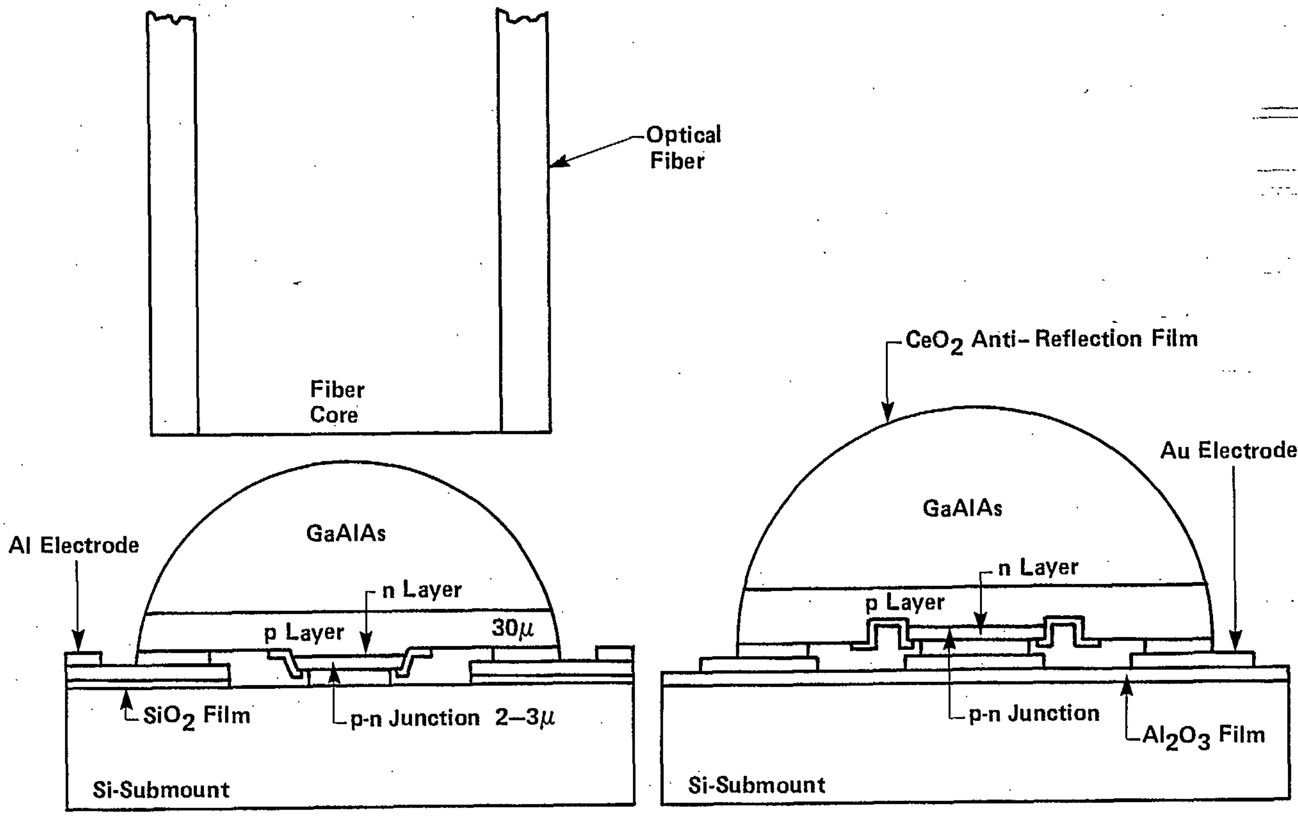


(II)

Figure 2.2 Light Emitting Diodes



(III)



(IV)

Figure 2.2 Light Emitting Diode (Cont'd)

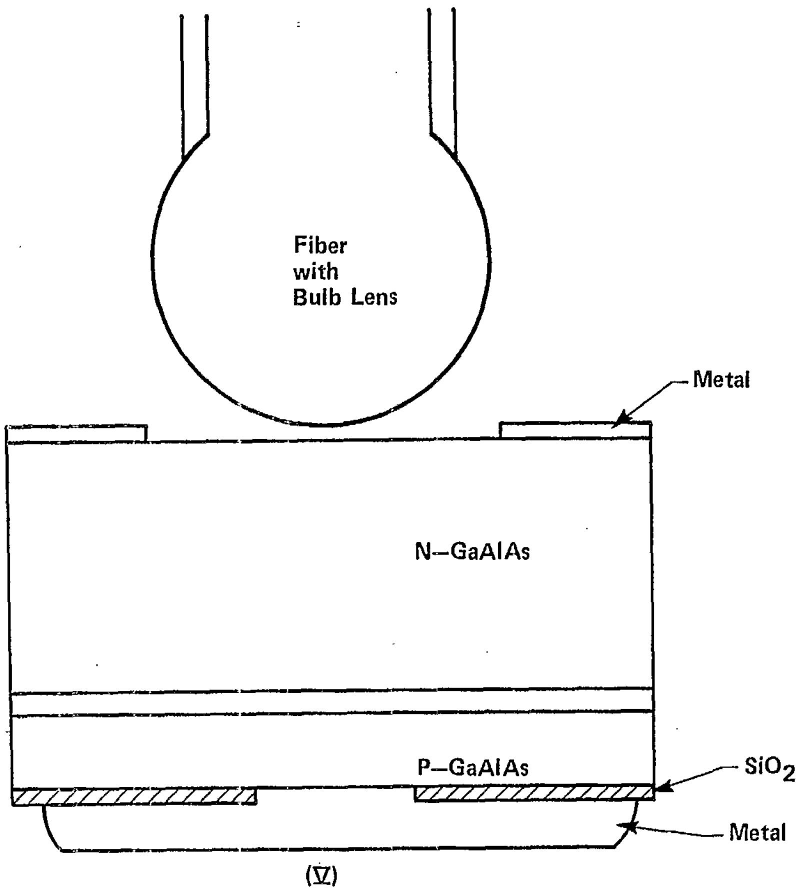


Figure 2.2 Light Emitting Diode (Cont'd)

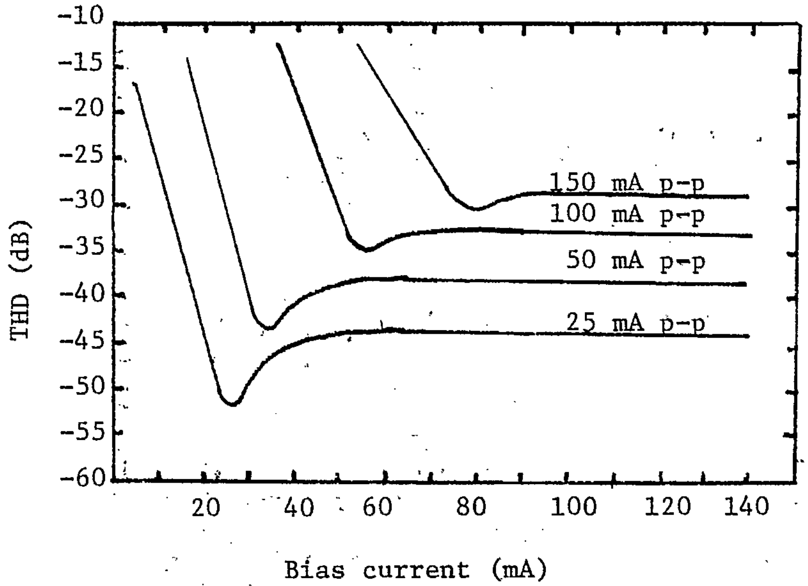


Fig. 2.3 Total Harmonic Distortion in a Typical Burrus Type Double Heterostructure LED

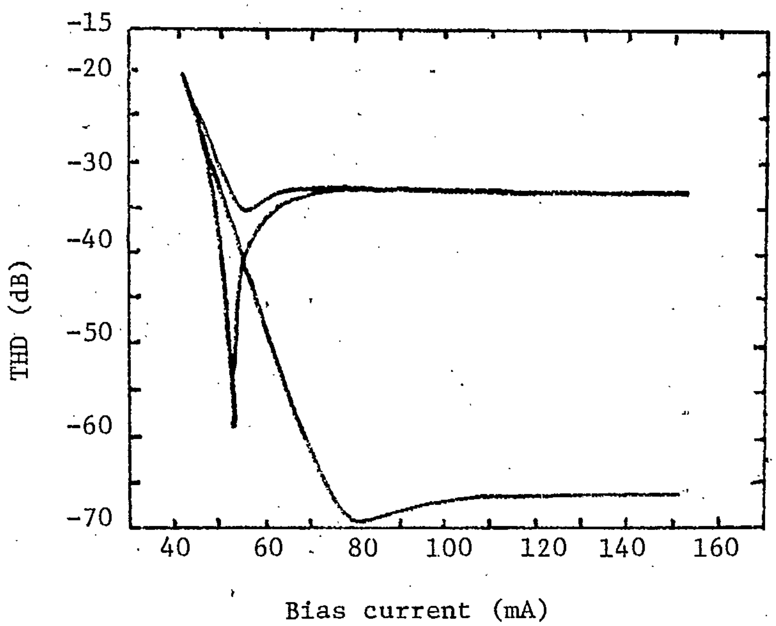


Fig. 2.4 Harmonic Components of a Typical Burrus Type Double-Heterostructure LED

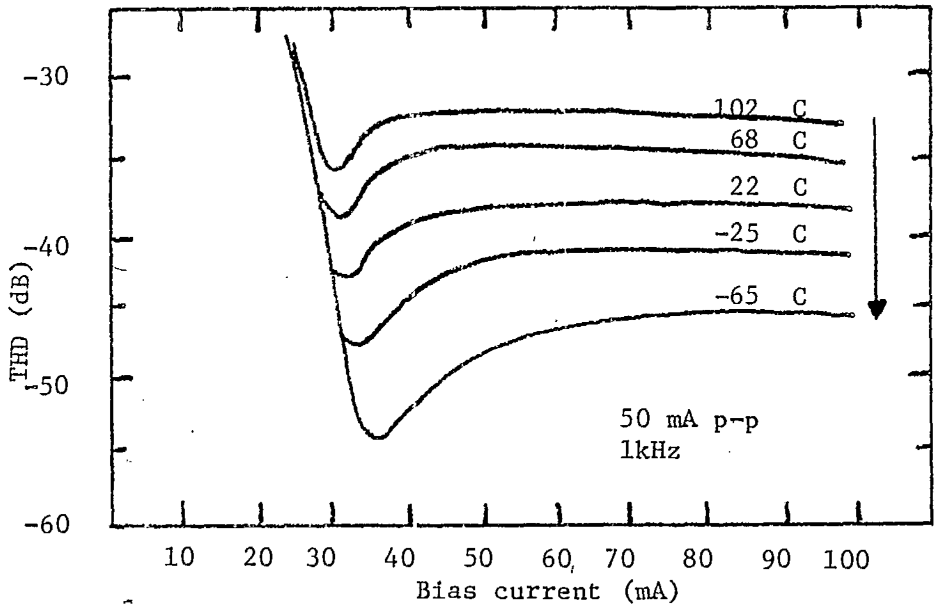


Fig. 2.5 Total harmonic distortion as a function of ambient temperature for a typical Burrus type double-heterostructure LED

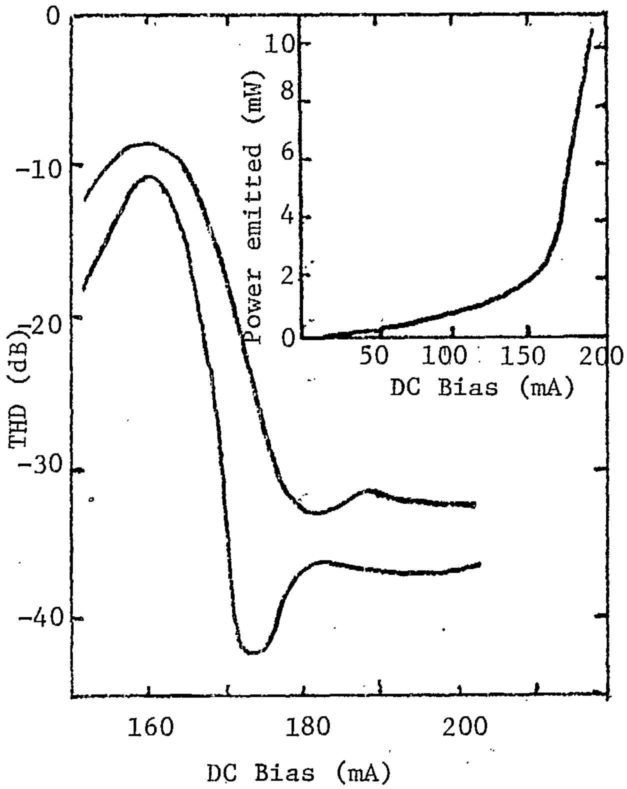


Fig. 2.6 Total harmonic distortion in a double-heterostructure injection laser. The insert shows the power emitted from one facet of the laser as a function of dc bias

3. LIGHT DETECTORS

by J. Conradi

3.1 INTRODUCTION

The emphasis in this section will be on silicon detectors for the wavelength region 800-900 nm. Mention will, however be made of developments that have taken place or can be expected in the 1.2 um region where the potential for future low loss, low dispersion fibers exists.

3.2 PROPERTIES ASSOCIATED WITH LIGHT DETECTORS

(a) Sensitivity (Quantum efficiency or responsivity)

The efficiency of a detector in converting optical power to electrical power is determined by its quantum efficiency defined as that fraction of incident photons that are converted to electrical current at the signal frequency. For well designed photodiodes the quantum efficiency in the 800-900 nm range will be 85-95%; at longer wavelengths, e.g., 1.06 um the quantum efficiency of silicon detectors has dropped to 10-20%, depending on the diode structure . Beyond 1.06 um detectors made of other materials such as Ge[2] or specific allows of various III-V or II-VI compounds have been developed, also with quantum efficiencies in the 80-90% range.

Increased sensitivity can often be obtained by using an avalanche photodiode, where the photocurrent undergoes avalanche multiplication.

In good silicon APDs avalanche gains 200 are obtainable. In other materials , gains of only 10-20 can be obtained before premature breakdown occurs.

(b) Noise

In receivers employing p-i-n photodiodes the dominant noise source will be the noise in the front end preamplifier except at high incident light levels where the shot noise in the photocurrent can dominate. In APDs, the multiplication process is an extremely noisy one. The excess noise generated depends on the avalanche gain, the APD structure and the material from which the APD is made . Quantitatively the noise power spectral density can be expressed as:

$$i_n^2 = 2e\ IM^2F \simeq 2e\ IM^x \quad (2 < x < 3) \qquad (3.1)$$

where

$$F = kM + (2 - 1/M\ (1-k)$$
$$\simeq 2 + kM \text{ for } k \text{ small and } M \text{ large} \qquad (3.2)$$

Here I is the detector bulk current before multiplication
(either bulk dark current or photocurrent)
M is the avalanche gain.
k is an effective ratio of the ionization rates of electrons and holes.

Thus, for best noise performance k should be as small as possible - it is this quality that is structure and material dependent. For a good silicon APD[1] $k \approx .02$ while for germanium[2] $k \simeq .5$. Other materials[5] have $k \approx 0.3-1$.

(c) Speed of Response

The speed of response of a photodiode in a detection circuit is limited either by the transit time of the photogenerated carriers across the depletion region or by the RC time constant of the circuit where C is the total input capacitance, made up of the capacitances of the preamplifier and detector. Only in very high speed applications above 400 Mb/s will the transit time be the limiting factor. The capacitance of p-i-n diodes suitable for single fiber applications can be < 0.1 pF while APDs will have capacitance $\simeq 0.5-10$ pF, depending on the diode structure, size and package. (see Tables 3.3.1 and 3.3.2)

(d) Size

Typical silicon chip size for both p-i-n and APDs is .030" x .030". Packaged devices come typically in TO-18 or TO-5 cans, althogh some devices are mounted in pill packages for good high speed performance.

(e) Thermal Stability

The reverse leakage current of both p-i-n and avalanche photodiodes will increase a factor $\simeq 2$ for every 10°C rise in temperature.

In the case of p-i-ns, this is of little consequence, while in the case of APDs the increased noise due to the increase in dark current can degrade the system performance somewhat. The breakdown voltage of avalanche photodiodes is also very temperature sensitive, and since these devices are often operated fairly close to breakdown, circuitry must be incorporated in the receiver to compensate for temperature changes. For constant avalanche gain, bias changes in the range .025 - 1.0 V/°C are required depending on the APD structure.

(f) Linearity

Provided reasonable bias is applied to p-i-n diodes to assure fast carrier sweep-out, non-linear effects are generally negligible even for analog broadband applications. With APDs, measurable non-linear effects arise due to avalanche gain reductions resulting from voltage drops across the load resistance and/or the space charge resistance in the diode, and also heating effects in which the increase in temperature resulting from the power being dissipated reduces the avalanche gain .

(g) Circuitry and Power Requirement

Basic bias circuit requirements are shown in Fig. 3.1. Facility must be provided for AGC and temperature compensation if an APD is to be used. Total power dissipated depends on the maximum incident power and the bias voltage of the APD. Worst case requirements would be ≃50 mW.

(h) Lifetime and Time Stability

For high voltage devices (e.g., APDs) the above parameters depend very much on how the diodes are packaged. Well packaged devices should last for many years without significant changes in their properties, and should be able to meet environmental and burn-in standards as specified in MIL-STD-883A.

3.3 DETECTORS AVAILABLE

Below are tables summarizing available silicon p-i-n and avalanche photodiodes. These are not intended to be exhaustive, rather the entries have been selected as being those devices that are available and that are suited for single optical fiber communications systems. In all cases, the data are from the manufacturer's specification sheets.

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TABLE 3.1

Summary of Silicon PIN Photodiode Characteristics

RESPONSIVITY (A/W)	@ (nm)	DARK CURRENT nA	@ V	RISETIME nSec	CAPACITANCE pF	AREA	MANUFACTURER & SER. NO.	PACKAGE
0.4	850	0.5	@ 10V	5	5	$2x10^{-3} cm^2$	UDT Pin-020	TO-18
0.5	900	5	@ 100V	3	2 @ 100V	1 mm dia.	EG&G SGD-040	TO-46
0.4	830	2	@ 10V		5	$0.5 mm^2$	Thompson CSF TCO-202	Special F/O Package
0.5	770	.15	10V	1	0.7	$.02 mm^2$	HP 5082-4205	Pill Package
0.65	800-900	10	45	3	2.5	$.8 mm^2$	RCA C30807	TO-18
0.55	840	1	45	1	0.6	.125mm dia.	BNR BNR D-5-2	TO-18 w.F/O

TABLE 3.2

Summary of Silicon Avalanche Photodiode Characteristics

QE(λ)%			AREA	I (DARK)		EXCESS NOISE FACTOR*	GAIN	RISETIME†	CAP.	V_b	$\frac{\Delta V_b}{\Delta T}$	MANUFACTURER & SER. NO.	PACKAGE
FAST	D.C.	λ	mm^2	BULK nA	SURFACE nA			nsec	pF		V/°C		
85	85	850	.8	.05	50	k =.02	150	1	3	325	1.1	RCA C30884	TO-5
40	65	820	.05	.5	10	x=2.3	200	80 GHz	1.2	170	.19	TI TIXL55, 56	TO-18 or pill
20	50	900	.2	.1	30	x=2.4	100	.5	5.5	200	.250	EMI S30500	TO-5
30	70	800	.03	.02		x∿2.35 k∿.04	200	.1	1.5	130	.14	NEC V384	Pill

*Expressed in terms of k for equation 3.2 or as a power of M

†Given as a 10-90% risetime for the fast component of the photocurrent or as a gain/bandwidth product

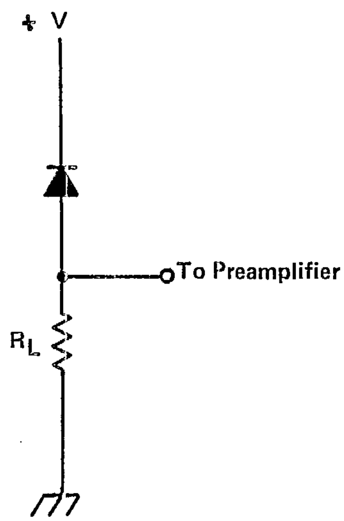

Figure 3.1 Bias Circuit for Photodiodes

4. OPTICAL FIBERS

F.D. King F.P. Kapron K. Abe

4.1 INTRODUCTION

Optical fibers employed for communications fall into three major categories.

1) Monomode
2) Multimode step index
3) Multimode graded index

Maximum information carrying capacity may be obtained using monomode fibers because of their zero intermodal dispersion ignoring very small effects du e to fiber ellipticity. However, the small core size and low numerical aperture characteristics of such fibers create difficulty in obtaining high coupled power and low splice and connector losses.

The majority of recent work has concentrated on the development of multimode fibers. Through the appropriate choice of numerical aperture and core size, adequate power for many system applications may be launched into such fibers even from non-coherent (LED) sources. Attenuation of 1/2 dB/km has been achieved[1], and by careful design of graded index structures, fibers with bandwidths of 2 GHz-km have been fabricated.[2]

4.1.1 Materials

Optical fibers can be classified into three categories depending upon the materials used in the construction of core and cladding.

High silica fiber
Compound glass fiber
Plastic clad fiber

Although a further category, that of all plastic fibers[3], exists, such fibers have high attenuation and will not be considered here. The principal materials used to fabricate the various types of optical fibers are shown in Table (4.1).

	CORE	CLADDING	REFERENCE
High silica fiber	Silica	Borosilica	4,5
	Silica	Fluorine doped silica	6
	Germanium doped silica	Silica	7
	Phosphorus doped silica	Silica	8
	Germanium doped borosilica	Silica or borosilica	9
	Phosphorus doped silica	Borosilica	10
	Titanium doped silica	Silica	11
	Aluminum doped silica	Silica	12
	Germanium and phosphorus doped silica	Silica	13
Compound glass fiber	Thallium borosilicate	Sodium borosilicate	14
	Sodium borosilicate	Sodium borosilicate	15
Plastic clad fiber	Silica	Fluorinated hydrocarbon plastics	16
	Silica	Silicone (or polysiloxane)	17

TABLE (4.1)

4.2 PARAMETERS OF OPTICAL FIBERS

The following are the most important parameters associated with optical fibers:

1) Attenuation
2) Numerical aperture
3) Core and cladding area
4) Pulse spreading and frequency bandwidth
5) Minimum radius of curvature
6) Tensile strength and percentage elongation
7) Environmental ruggedness

Each of these parameters will be defined and its significance briefly summarized.

4.2.1 Attenuation (A)

$$A = 10 \log_{10} \frac{Pout}{Pin}$$

where

- A = attenuation (in dB) of length L of fiber with a specified source
- P_{in} = power launched into length L (detected after $L_0 \simeq$ few meters)
- P_{out} = power detected after length L

Generally, fiber attenuation is the result both of absorption and of scattering loss. The absorption loss results from proximity to the UV absorption edge and from impurities. Contributions are made to the scattering loss both by intrinsic Rayleigh scattering and by scattering at imperfections resulting from the fabrication process (flaws, microbends etc.). The first factors in both cases determine the ultimate low which may be obtained in fiber attenuation.

For most practical purposes, only the total measured attenuation is of interest. This will be a function of the source wavelength and the launching conditions[18]. Furthermore, results of individual measurements may depend on the fiber winding condition and the nature of the cable or plastic jacket.

In this review attenuation values are reported for a wavelength between 0.8 and 0.85 μm since the most available practical sources emit in this wavelength range. Future work may move toward 1.3 um where observed fiber attenuation[1] and predicted chromatic dispersion[19] are both very low.

4.2.2 Numerical Aperture (NA)

$$NA = N_o \sin \Theta_{MAX} = \sqrt{n_1^2 - n_2^2}$$

where

- N_o = refractive index of launching medium
- Θmax = maximum acceptance half angle of fiber at center axis (see 2.2 Radiance)
- n_1 = core index at center axis
- n_2 = cladding index

For multimode fibers with Lambertian sources, the maximum power which may be coupled into the fiber is[20] proportional to $(NA)^2$. Fon non-Lambertian sources, generally, the power which may be launched increases with NA. However the emission pattern and refractive index profile must be taken into account.

For practical purposes, the NA of a fiber with a specified light source is defined by the cone half-angle θ which contains 90% of the output power[7]

In step index fibers the modal dispersion increases with NA^2 and in optimized graded index fibers[20] with $(NA)^4$.

4.2.3 Core Area (A_c)

For step index fibers flat butted to Lambertian emitters whose emitting area A_E is larger than A_c, the optical power which may be coupled is proportional to A_c. For $A_c > A_E$ the flat butt coupling efficiency is independent of A_c; however, in this case the efficiency may be improved by using a lens ended fiber[21] or a taper-ended fiber[22]. For graded index fibers with Lambertian sources, an optimum A_c/A_E may be calculated[23]. Core area alone is generally of less importance when coupling from the small emiting areas typical of laser sources.

Because of the difficulty in exactly aligning small core areas, the core size influences the insertion loss of many splice and connector designs.

4.2.4 Pulse Spreading and Frequency Bandwidth

Monochromatic or intermodal dispersion (sometimes loosely termed "modal dispersion") is due to the variation of group velocity with mode. It is reduced with smaller NA's, with mode mixing, and with index profiling; it is eliminated with monomode operation, neglecting, once again, small effects due to fiber ellipticity. Chromatic or intramodal dispersion (sometimes loosely termed "material dispersion") is due to the variation of group velocity with wavelength. In high silica fibers, it is reduced by using sources which emit in the 1.3 um wavelength region[18] or, at lower wavelengths by using sources with narrow spectral widths.

Pulse spreading may be defined as:

$$\Delta t = \sqrt{(\Delta t_L)^2 - (\Delta t_o)^2}$$

where Δt_L and Δt_o are respectively the RMS or 3 dB pulse widths exiting from a long length L and a short length of the same fiber. (Source and detector spreadings subtract out.) The two dispersion effects contribute as

$$\Delta t = \sqrt{(\Delta t_M)^2 + (D\,\Delta\lambda)^2}.$$

The intermodal component t_M has been measured below 0.2 ns/km,[1] though 1/2 ns/km is more common. It increases linearly with length up to equilibrium length L_e; around $L \approx L_e$ there is a gradual transition to $L^{.5}$ behaviour. The chromatic component is $D \cong 0.09$ ns/km-nm near 835nm for silica alone[24]; this will rise fractionally with doping and modal effects and is linear with length.

Frequency bandwidth Δf is usually defined by the 3 dB rolloff of the electrical transfer function of the fiber (which is the square of the fiber optical transfer function) measured with a CW frequency sweep. Intermodal and chromatic effects enter here also.

Pulse spreading (3 dB optical) and frequency bandwidth (3 dB electrical) are closely related by[25].

$$\Delta f \text{ (MHz - km)} \times \Delta t \text{ (ns/km)} = 311$$

4.2.5 Minimum Bend Radii

Two minimum bend radii are of importance for optical fibers. The first, the minimum band radius to fiber breakage is, for typical high silica plastic coated fibers, a few mm. The second minimum bend radius is a system or cabling parameter which describes the minimum bend radius which may be inserted in the fiber without causing unacceptable loss in transmission.

For smooth bending, the bend radius (R) which gives 3 dB attenuation is approximately[26].

$$R = \left(\frac{2}{NA}\right)^2 D$$

where D is the core diameter. Fibers with small core and large numerical apertures are thus less susceptible to bending losses. While for single bends, minimum bend radii of this order might be tolerated, for multiple bends, such as are encountered during stranding for cable fabrication, minimum bend radii must be at least 10R.

4.2.6 Tensile Strength and Elongation

The ultimate tensile strength of silica is known to be higher than 2×10^6 psi[27]. However, surface flaws caused by scratches or inclusions may considerably reduce the measured values for optical fiber. By careful choice of preform fabrication, pulling, and surface protection techniques, tensile strengths of approximately 8×10^5 psi over 20 meter sample lengths have been obtained[28]. Such suitably coated and protected fibers can withstand more than 3% elongation before breaking.

4.2.7 Environmental Ruggedness

To preserve the tensile strength characteristics of optical fibers, a protective surface coating must be applied during the pulling process. Cable structures must be designed such that the fibers are not subjected to stresses and strains either during fabrication or as a result of long term environmental exposure or mechanical abuse.

Neutron and gamma radiation may directly increase the fiber attenuation by creating damage centers, and this may be significant in very high radiation environments. However, normal dosage of background radiation at the earth's surface is not expected to show a significant effect in doped silica fibers over several centuries[29].

4.3 FIBER PARAMETER VALUES

Table (4.2) lists the principal characteristics of some available low loss optical fibers. Optical fiber cable development is rapidly moving to the point where the optical characteristics of the cabled fiber are the same as those before cabling. For this reason properties of cabled fibers are not considered separately.

Table (4.3) shows characteristics of a number of examples of new or improved fiber structures and materials which are being developed.

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TABLE 4.2 - Principal Characteristics of Some Presently Available Low Loss Optical Fibers

COMPANY	TYPE	CORE MATERIAL	CLADDING MATERIAL	CORE DIAMETER μm	ATTENUATION (dB) at λ (μm)	NA	PULSE DISPERSION ns/km	REFERENCE OR PRODUCT NO.
ITT	Step	Silica	Plastic	125	40 at .79	0.25	50	PS-05-40
Fujikura	Step	Silica	Silicone	130 or 150	5-10 at .82	0.4	10	
Valtec	Step	Silica	Plastic	125 or 250	20 or 40	.22-.30	<40	PC-05,-40
Corning	Step	Ge doped silica	Silica	85	10 or 6 at .82	0.18 (NA_{90})	17	Fibers Product Bulletin No. 2
Fiber Communications Inc.	Step	Silica	Borosilica	55 or 78	20 or 10	0.16		
ITT	Step	Doped silica	Doped silica	50	12	0.25	30	GS-02-10
Valtec	Step			65 or 130	<10 at 0.82	0.20	<30	MS-05 or MS-10
Fibres Optiques	Step			90	<15 at 0.8-0.85	0.13	17	
Galileo	Step	Doped silica		60	10 at 0.82	0.2		Galite 5000, data sheet
BNR	Step	Doped silica	Silica	100	15 at 0.84	0.20 (NA_{90})		7-1-A
Nippon Sheet Glass	Graded	Thallium Borosilicate	Sodium Borosilicate	35	5-20	0.19	.83	SELFOC
Valtec	Graded			65 or 130	<20	0.2	<10	MG-05-01
Corning	Graded	Ge doped silica	Silica	62.5	10 or 6 at 0.82	0.16 or 0.20 (NA_{90})	1.7 or 0.8	Fibers Product Bulletin No. 2
BNR	Graded	Doped silica	Silica	100 or 75	15 or 8 at 0.84	0.22 (NA_{90})	3 or 1.5	7-2-A or 7-2-B
Valtec	Mono-mode			5-15	<20		<1	SM-10
Fiber Communications	Mono-mode				2.5	250 at 0.63	0.10-0.12	

TABLE 4.3- Examples of New or Improved Fiber Structures and Materials Under Development

REFERENCE	TYPE	CORE MATERIAL	CLADDING MATERIAL	STRUCTURE	ATTENUATION dB/km	NA	PULSE DISPERSION ns/km	NOTABLE FEATURE
K. Inada et al 2nd Europ. Conf. Opt. Comm. 1976	Step	Silica	Silicone	Plastic clad	4 at 0.83 µm at NA 0.15	0.32	10	Low attenuation and pulse spreading for plastic clad fiber
P. Kaiser et al., Appl. Opt. 14, 156 (1975)	Step	Silica	Teflon FEP	Loose sleeve plastic clad	14 at NA 0.3	0.35	30	Low attenuation simple low cost structure
K.J. Beals et al, Proc. IEE 123, 591 (1976) SELFOC	Step	Sodium	Borosilicate	Compound Glass	6.6 at 0.83µ	0.17	20-30	Low attenuation for compound glass fiber
S. Kobayashi et al, Elec. Lett., 10, 410 (1974)	Step	Aluminum doped silica	Silica	High silica	10 at .66µm	0.09		Aluminum doping of core
Abe, 2nd Europ. Conf. Opt. Comm.	Step	Silica	Fluorine doped silica	High silica				Fluorine doping of cladding
Osanai et al 2nd Europ. Conference	Graded	Phosphorus	Silica	High silica	1.6 at 0.83		1.2	Phosphorus doping of core, low attenuation (0.4 dB/km, at 1.3 µm) <1 dB/km between 1.16 and 1.68
W.G. French Appl. Opt. 15, 1803 (1976)	Graded	Silica	Borosilicate	High silica	3dB at 0.9µm	0.14	0.18	Low pulse dispersion

TABLE 3 (Cont'd)

L.G. Cohen Topical Meeting on O.F. Williamsburg 1975	Single	Silica	Borosilicate	High silica	2.5 dB at 0.83 µm	0.076	<0.4	Low attenuation in single mode fiber
T. Nakahara et al, 2nd European Conference	Ring core step & graded, mono-mode & multi-mode	Germania doped silica	silica	High silica	3-10 at 0.85	0.1-0.17	<0.15 to 10	Claimed easier fiber-fiber coupling
K. Mikoshiba et al, 2nd European Conference	W			High silica				Smaller loss increase with bends and mechanical stress; larger mono-mode core

5. OPTICAL FIBER CABLES

by B.L. Board

5.1 SCOPE

Since the present study will deal solely with transmission of signals by fiber optics over long distances, the review of fiber cables will omit discussion of multi-fiber bundle type cables. These cables, where the same optical signal is carried by many fibers in parallel along the same route, find their principal application in very short systems, such as in-building links. Our attention will turn, rather, to cables designed to house and protect one or several fibers, each capable of transmitting an independent message and throughout the discussion such usage will be assumed. For the same reason, only cables which contain fibers of low or intermediate loss will be considered.

5.2 CABLE CONSTRUCTION

The cable must provide mechanical and environmental protection to the fibers both in storage, during installation, and during the cable's operational life - three phases which impose quite distinct requirements on the cable. To be compatible with current telephone cables from the point of view of maintenance, it should be noted that an operational life of up to 40 years is required. Despite the requirements for adequate protection, though, the additional bulk added to a bunch of fibers by the cabling process should be minimised, and an over-rigid structure avoided in order to preserve two of the more attractive features of fiber optics, namely small physical size and mechanical flexibility.

5.2.1 Metallic Elements

One of the advantages of optical fiber transmission is the immunity of the optical performance of fibers to external electromagnetic effects, including:

(i) electrical interference

(ii) lightning strikes and induced electrical power surges on communications transmission lines.

The use of metallic elements in the cable for strength members, for provision of power to repeaters, remote stations, etc., for signalling, for auxiliary communications for grounding, or in welded layers for moisture protection barriers such as aluminum-laminated plastic sheaths eliminates much or all of this significant advantage.

5.2.2 Fiber Constraint

Many cable designs permit the fibers to move relative to the sheath, and even relative to each other in some cases. Other designs prevent fiber movement. The latter type of cable requires a high longitudinal elastic modulus in order to limit the elongation of the cable, and therefore the enclosed fibers, to a value less than the fiber elongation limit -- a relatively difficult requirement to meet. Also, it is difficult to avoid introducing significant cabling losses.

The fibers can be constrained by filling the core, typically by an extrusion process, or by sandwiching the fiber layer(s) tightly between 'cushions' or bindings.

Freedom of movement of fibers is commonly provided by extruding a loose tube over the coated fiber prior to cabling (the tube becomes, in effect, a loose secondary or coating), or by locating the fibers in grooves or channels on the surface of a 'spacer'.

5.2.3 Fiber Arrangement

A variety of geometrical arrangements for fibers in cable are currently used, and stranding (incorporating a helical lay) is a common practice with all arrangements. The arrangements can be classified as such:

(a) Circular Layer -- the fibers are stranded in a circular layer around a central core (or alternatively a grooved spacer), and further concentric layers are added to make cables with many fibers. The fibers in each layer can either be close-stranded (touching) or spaced apart. It is necessary to apply a suitable shock-absorbing material ('Cushion') between the layers to prevent microbending.

(b) Unit approach -- this approach attempts to avoid the problems involved in multi-layer cabling when cabling large numbers of fibers. A relatively small number of coated fibers are grouped in a cable format and a reinforced protective sheathing applied. This sub-cable is commonly termed a 'unit'. Units are stranded together in the required numbers, with strength members and sheath, to form a cable.

(c) Ribbon or tape -- the fibers are arranged and encapsulated in a flat ribbon within the cable.

(d) Array -- ribbons of fibers are stacked (and then stranded) to produce a square or rectangular array of fibers. It is claimed that this approach lends itself well to cabling large numbers of fibers and to mass splicing techniques.

5.2.4 Strength Members

Optical fibers can withstand only relatively small tensile forces, and their ability to elongate is very limited. Thus the required tensile strength of a fiber cable must be specifically provided by alternative elements within the cable. This is usually done by including a strength member(s) in the cable, though some designs feature a strong and relatively stiff sheath which provides the necessary strength. Kevlar, F.R.P., polyethylene terephthalate, and steel are common strength member materials. However, metallic members have drawbacks of an electromagnetic nature, and non-metallic members appear more popular for many applications.

Strength members can be located at the centre of the cable core, or directly beneath the sheath, or helically stranded or even braided, in the case of materials such as Kevlar, around and concentric with the stranded fibers.

5.3 MECHANICAL PROPERTIES

5.3.1 Tensile Strength

The tensile strength of the cable must be sufficient to enable the cable to be installed without damage, and, once installed, to withstand common and predictable loads placed on it during its operating life. Therefore the strength requirement is determined by the maximum tensions encountered. For cable installed in underground ducts, maximum tensile loading usually occurs during installation (a pullin operation), the pulling tension being a function of the cable sheath coefficient of friction and the cable unit mass, as well as the duct route itself. If assumptions are made regarding the types of underground applications for a cable and the parameters involved, the expected pulling tensions can be estimated and the required cable tensile strength based on these estimates.

For aerial applications, the cable will incur significant tensile loading during normal operation, such as wind, ice, and snow loadings, animal and bird weightings, as well as during installation. Cable unit mass, diameter, and sheath surface "smoothness" will be important factors in determining the magnitude of such loads, and therefore the tensile strength required.

5.3.2 Bending Raduis

The minimum radius to which a cable can be bent without damage is a measure of the suitability of the cable for various applications. Cable to be used in underground ducts or aerial routes must withstand the relatively severe requirements of installation and shipping, and the effects of accidental bending. This type of cable therefore requires a relatively small allowable bending radius. For cable installed in buildings, the geometry and construction of the route typically impose more stringent demands on the cable, and the minimum bending radius must be small. The ability of a cable to withstand repeated bending at this radius without damage is a measure of its flexibility. Fiber cable flexibility is improved by incorporating a helical lay of appropriate pitch in the fibers and by a judicious choice of cable materials.

5.3.3 Crush Resistance

The crush resistance is a measure of the ability of the cable to survive static, distributed lateral loads. These loads include sidewall pressures in duct bends and on pulling sheaves during underground and building installations, wind and ice lateral loadings with aerial cables, and accidents such as stepping on the cable or equipment resting on the cable during installation. These loads, particularly accidental ones, can be relatively large, and the cable should withstand them.

5.3.4 Impact Strength

The impact strength is a measure of a cable's ability to withstand lateral impact loads. Cables, regardless of the application, experience accidental impacts during shipping and storage, during installation and splicing, and during their operating life, and should have a reasonable degree of immunity to such mishaps.

5.4 ENVIRONMENTAL STABILITY

5.4.1 Temperature

Careful choice of cable materials during design will enable fiber cables to withstand a wide range of temperatures without physical damage to cable or fibers. However, the optical transmission properties, such as attenuation and dispersion, of many fibers exhibit a significant temperature dependence usually associated with shrinkage effects of the fiber coating. It is therefore desirable that the cable design provide as much thermal isolation to such fibers as is possible within the design constraints.

5.4.2 Moisture

There is fairly general agreement that glass exposed to moisture suffers surface attack, the extent of the attack being dependent on the glass composition; if the glass is under stress it will eventually fracture. However, there exists uncertainty about the effect of prolonged exposure on non-stressed glass. The most recent and relevant investigation by Corning Glass Works concludes that moisture has negligible effect on coated, doped-silica fibers if the fibers are not stressed. However, many results remain inconclusive, and much work has yet to be done to determine whether moisture penetration in compound glass or high-silica glass fiber cables significantly affects fiber strength or other properties over an extended period of time.

The degree of moisture penetration to fiber cladding surfaces in cables is dependent on the fiber coating and cable core filler and sheath materials, and on the cable design itself. Nor can the problems be ignored by specifying a sheath material that is impervious to moisture (this includes aluminum barrier laminations).

Accidental tearing or puncturing of the sheath can occur during and after cable installation, pinholes occur in plastic extrusions during manufacture, and insects, rodents, and chemicals can attack cables during service.

It is desirable that the cable design prevent migration of moisture along the core amongst the fibers, as this will compound any undersirable effects moisture penetration may have. Filled-core designs attempt to prevent such migration.

5.5 SURVEY OF DEVELOPMENTAL CABLES

Refer to Table 5.1

Fiber coatings described are tight-fitting unless otherwise indicated. The temperature range is the range over which the cable and fibers incur no damage; it is not the range over which the optical transmission properties remain stable.

5.6 AVAILABILITY

5.6.1 All of the cables listed in Table 5.1, except those of Bell Telephone Labs, Hitachi Cable, and Cables de Lyon, are offered for sale. The latter two exceptions expect to market cables in 1977, though there is no indication that these will be the same cables as those described in Table 5.1.

5.6.2 The marketing details of currently-available cables are:

(a) I.T.T. Components (or STC), U.K.:

OFC-SIG-X-60 is available in lengths up to 500 m. The 6-fiber version costs (C) $15.99/m with a delivery time of 6-8 weeks. The Canadian representative is I.T.T. (Canada) Components.

(b) I.T.T. (Roanoke), U.S.A.

GS-20H cable costs (C) $15.79/m (5 fibers guaranteed), or $19.73/m (6 fibers guaranteed). The maximum continuous length is 500 m, with delivery of 30-60 days F.O.B. I.T.T. (Canada) Components is the Canadian sales representative.

(c) Corning Glass Works, U.S.A.
Corguide #1330 costs (U.S.) $10/m and #1302 costs (U.S.) $13.50/m. Both are available in premium grades of

10dB/km for an extra (U.S.) $5.25/m, while #1302 is also available with 400 MHz-km fibers for a premium also of (U.S. $5.25/m. Maximum lengths of 1 km are quoted, with an order time of 30 days F.O.B.

(d) Furukawa Electric Industries, Japan
Their 4-fiber cable is available for 12,000 yen (approx. $40)/m in maximum lengths of 500m.

(e) Fujikura Cable Works, Japan
Their silicone-clad fiber cable is available for approx. $12/m (Japan price) for 6 fibers. Maximum lengths of 1 km are available.

(f) Sumitomo Electric Industries, Japan
SCP cable is available in lengths of up to 500m. No prices available. They have a branch office in Montreal.

(g) Valtec, U.S.A.
MS and MG type cables are priced at (U.S.) $2.50/m, and available in lengths exceeding 1 km. The Canadian agent is Power Service Products (Ontario).

(h) B.I.C.C., U.K.
No information available.

(i) Fiberoptic Cable Corp., U.S.A.
Q1R-1-10 is priced at (U.S.) $1.75/m, and Q2R-1-10 at $3.50/m. Maximum continuous length of 1 km, with 30 days F.O.B.

(j) Fiber Communications Inc., U.S.A.
Fiberguide S-10 and S-20 are priced at (U.S.) $3.00/m for 500m lengths. 1 km lengths are available on special order.

5.6.3 Fiber cable technology is still very much in the developmental stage. Those cables that are available commercially are, in effect, prototype cables. Changes in cable design and construction and fiber technology, affecting optical and mechanical performance and price, can be expected to continue.

5.6.4 Numerous organizations throughout the world are working on communications cable development but have yet to reveal sufficient details regarding their progress or their future production/marketing plans. They include C.N.E.T. (France), General Electric Company (UK), Pirelli Industries (Italy), Dainichi-Nippon (Japan), Siemens (Germany), and General Cable Corp. (USA). It is reasonable to anticipate that some of these organizations will manufacture and market cables in the future.

TABLE 5.1 SURVEY OF DEVELOPMENTAL CABLES

Organization	I.T.T. Components U.K.	I.T.T. (Roanoke) U.S.A.	Corning GlassWorks, U.S.A.	Furukawa Electric, Japan	Fujikura Cable Japan	Sumitomo Electric Japan	Valtec U.S.A.
Cable designation	OFC-SIG-X-60	GS-20H	Corguide #1300(a) #1302(b)	--	--	SCP	(a) MS (b) MG
Fibers - quantity	4,6,8	6	7	4	4-12	4	1
- manufacturer	S.T.L.	I.T.T. (Roanoke)	Corning	Furukawa	Fujikura	Nippon Sheet Glass	Valtec
- SI or GI	S	S	(a) S, (b) G	S	S	G (Selfoc)	(a) S (b) G
- N.A.	0.5	0.25	(a) 0.18, (b) 0.16	0.15	0.4	--	0.2
Max. Attenuation (dB/km)	<60	18	20	10	5-10	10	(a) ≤10, (b) <20
Dispersion (nS/km)	--	30	--	--	10	--	(a) <30, (b) <10
Bandwidth (MHz/km)	--	--	(a) 20, (b) 200	--	--	--	--
Fiber coating - diameter (μm)	~1000	500	132	~900	800-1000	--	no coating
- material(s)	polyethylene	silicone, Hytrel	Kynar	nylon	nylon	--	" "
Method of containing fiber	non-filled	non-filled	loose in individual tubes	non-filled	non-filled	non-filled	loose in tube
Geometrical arrangement of fibers	close stranded	stranded	close stranded	stranded	close stranded	stranded	N/A
Strength member(s) - material	PE Terephthalate	Kevlar	Kevlar (two)	FRP	FRP	FRP	Kevlar
- location	centre	centre	180° apart, planar	centre	centre	centre	concentric with fiber
Sheath material	polyethylene	polyurethane	polyurethane	LAP	LAP	LAP	Hytrel
Cable diameter (mm)	6-7	5.5	5	7.7	14	19	4.1
Unit mass (kg/km)	33	30	25	30	~130	230	16
Tensile Strength (N)	<490	980	490	196	980	590	670
Crush Resistance (N/m)	--	--	--	11780	--	--	--
Impact strength (N.m)	--	--	1.4	4	--	--	--
Min. Bending Radius (mm)	50	50	25	46	300	500	--
Temp Range (°C)	0 to +70	--	-55 to +85	--	--	--	-50 to +100

All maximum attenuation figures are at wavelengths in the 800-900 nm range
LAP : Aluminum-laminated polyethylene
N/A : not applicable
-- : indicates information not available

TABLE 5.1 (CONT)

Organization	Fiber Communications (F.C.I.), USA	FORT, France	Hitachi Cable Japan	Bell Telephone Labs, USA	B.I.C.C., UK	Fiberoptic Cable Corp(FOC),USA	Câbles de Lyon France
Cable designation	Fiberguide	TIS-LD	(a) Underground (b) Aerial	--	--	(a) Q1R-1-10 (b) Q2R-1-10	--
Fibers - quantity	1	(a)3, (b)7, (c)19	4	144	2,6	(a) 1,(b) 2	(a)19, (b)37
- manufacturer	FCI?	FORT?	Hitachi(W-type)	Western Electric	Corning	FOC	Corning
- SI or GI	S	Pseudo G	S or G	G	(a) S, (b) G	S	S or G
- N.A.	0.16	0.17	--	--	(a)0.16,(b)0.13	0.25	0.18(S), 0.15(G)
Max. Attenuation (dB/km)	40	30	--	6(average)	15-20	20	4.6(S), 5.2(G)
Dispersion (nS/km)	--	--	--	--	(a) 35,(b) 10	30	--
Bandwidth (MHz/km)	20	100	50(SI), 100(GI)	550(average)	--	--	--
Fiber coating - diameter (μm)	~500	900-1000	--	--	132	--	850
- material(s)	plastic	silicone, Hytrel	--	--	Kynar	plastic	Kynar, loose polyamide
Method of containing fiber	encapsulated by sheath	non-filled	loose in grooved plastic spacer	non-filled	loose in square tube	loose in tube?	loose in secondary coating
Geometrical arrangement of fibers	N/A	stranded	stranded on spacer	12X12 array	--	--	close stranded in layers
Strength member(s) - material	Sheath acts as	Kevlar	(a)FRP (b)steel	braided Kevlar?	steel (two)	Kevlar	sheath
- location	strength member	concentric braid	centre	concentric	180^{o} apart, planar	concentric	"
Sheath material	PE terephthalate	polyurethane	(a)PE (b)LAP	plastic	polyethylene	Hytrel	LAP
Cable diameter (mm)	2	(a)5.5,(b)6, (c)8	(a)17 (b)22	12	7.7x4.3(oval)	(a)3.75,(b)5x8.75	(a)17, (b)22
Unit mass (kg/km)	2.1	--	--	93	--	(a)7,(b)15	--
Tensile Strength (N)	2110	(a)295,(b)540,(c)590	390	1800	--	(a)226(b)442	3000
Crush Resistance (N/m)	--	--	1200	--	--	--	--
Impact strength (N.m)	--	--	4	--	--	--	--
Min. Bending Radius (mm)	50	(a)80,(b)80,(c)100	(a)102 (b)132	--	--	(a) 25(b) 30	--
Temp Range (^{o}C)	--	-40 to +120	--	--	--	-50 to +150	--

All maximum attenuation figures are at wavelengths in the 800-900 nm range
LAP : Aluminum-laminated polyethylene
N/A : not applicable
-- : indicates information not available

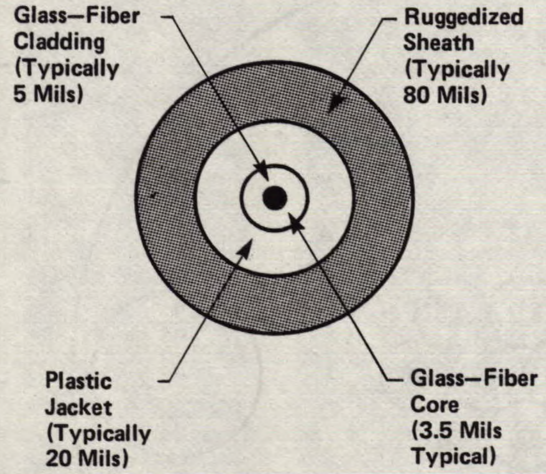


Figure 5.1 Fiber Communications Fiberguide 'Cable'

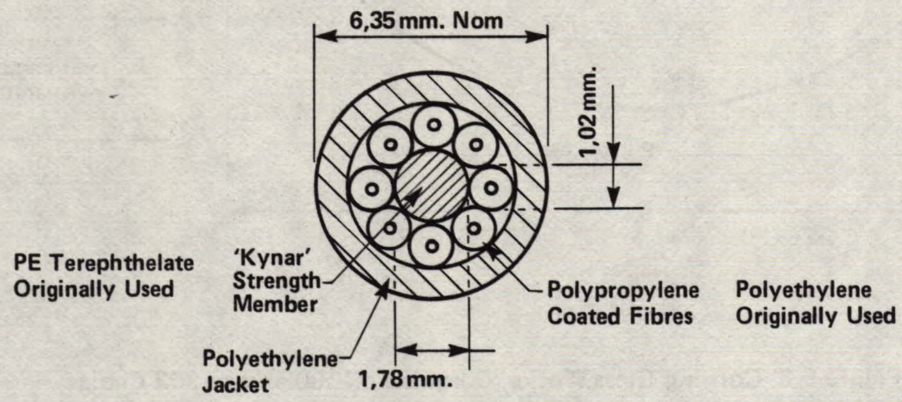
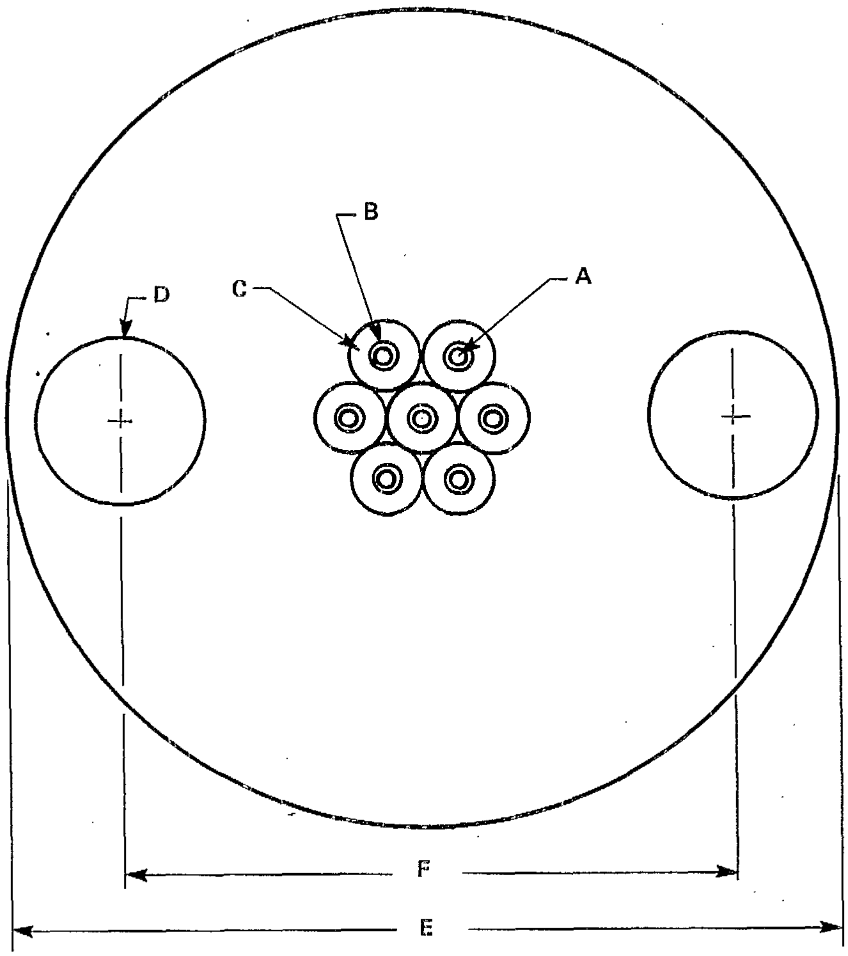


Figure 5.2 I.T.T. (U.K.) OFC—SIG—8—60 Cable



Key		(Dimensions in mm)
A	Core Diameter: Step Graded	 0.085 0.062
B	Corguide Fiber Outer Diameter (Kynar Coated Corguide Fiber Diameter)	0.125 0.132
C	Buffer Diameter	0.380
D	Strength Member Diameter	0.970
E	Cable Diameter	5.00
F	Strength Member Separation	3.63

Figure 5.3 Corning Class Works Corguide #1300 and #1302 Cables

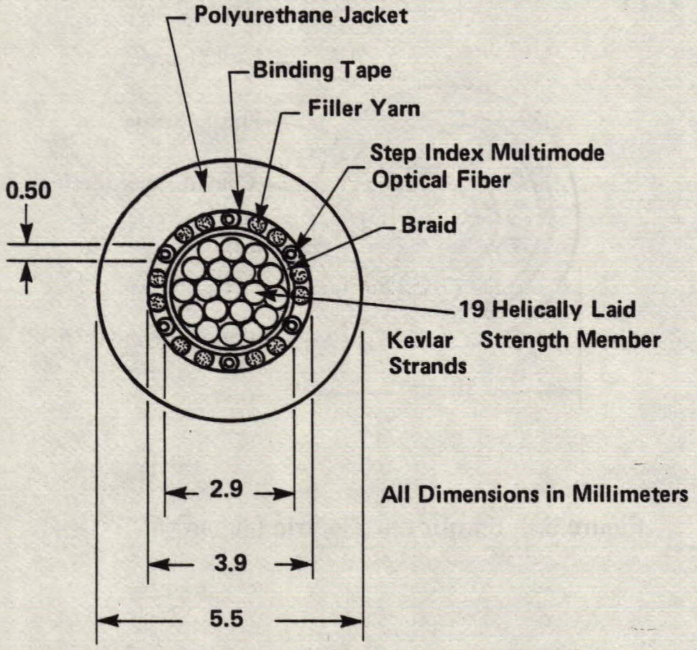


Figure 5.4 I.T.T. (Roanoke) GS–20H Cable

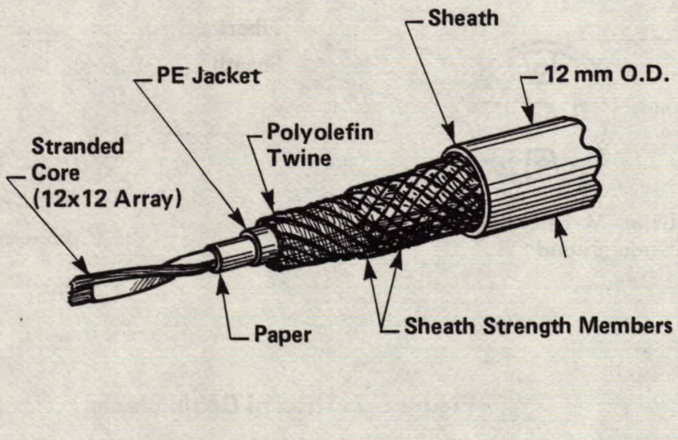


Figure 5.5 B.T.L. 144 Fiber Cable

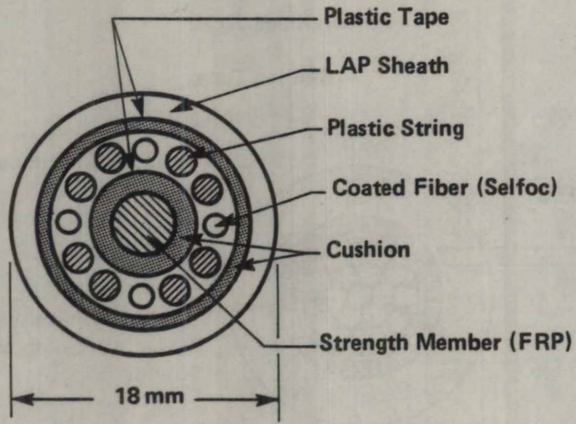


Figure 5.6 Sumitomo Electric (Japan) SCP Cable

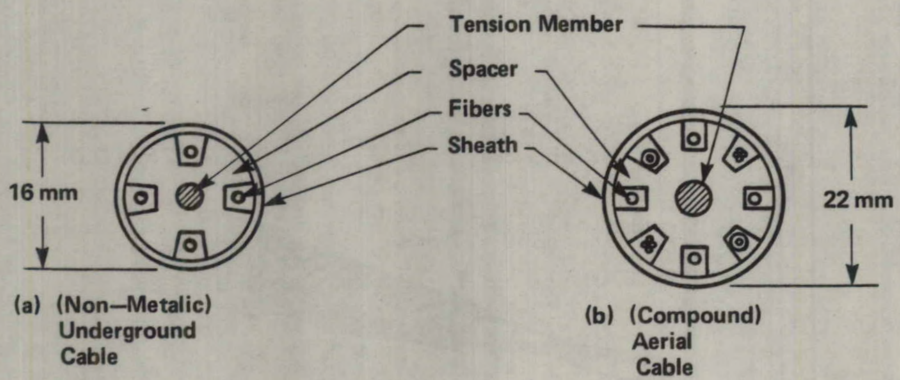


Figure 5.7 Hitachi Cable (Japan)

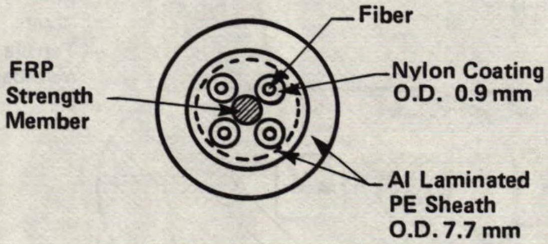


Figure 5.8 Furukawa Electric (Japan) — 4 Fiber Cable

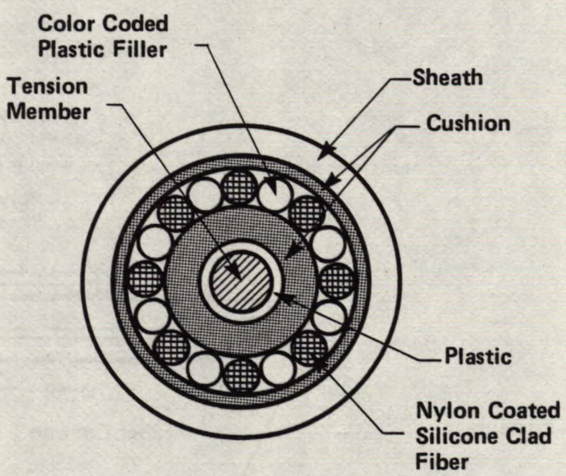


Figure 5.9 Fujikura Cable (Japan) — 4—12 Fibers

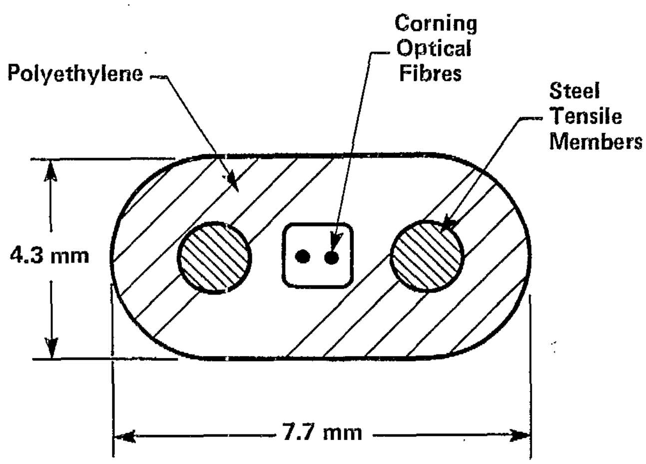


Figure 5.10 B.I.C.C. (U.K.) Cable (2 Fibers)

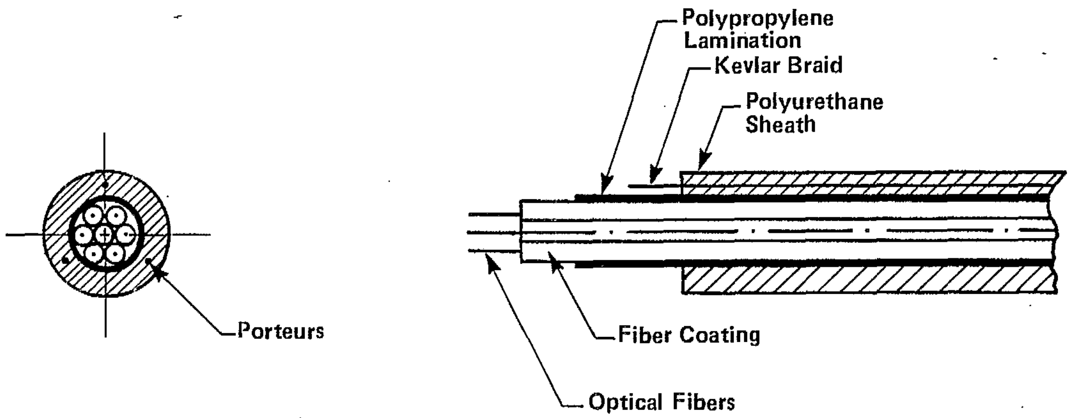
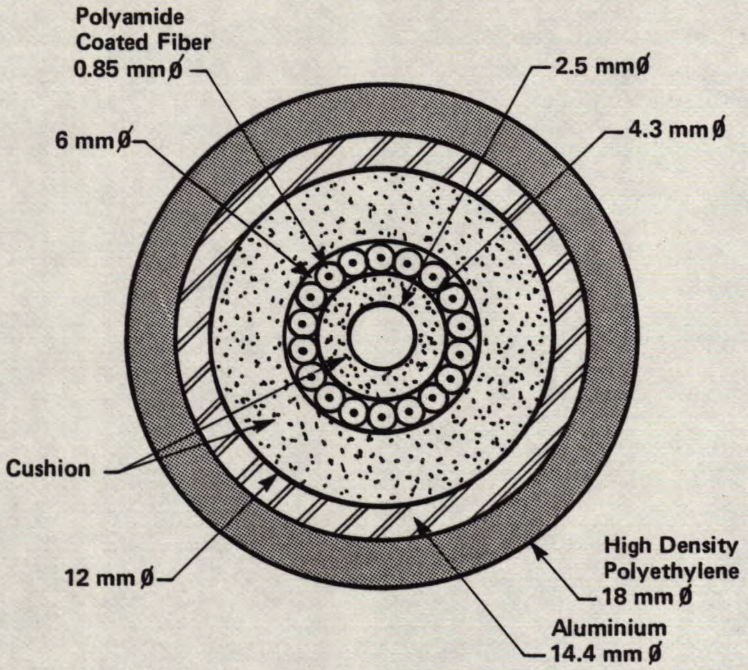
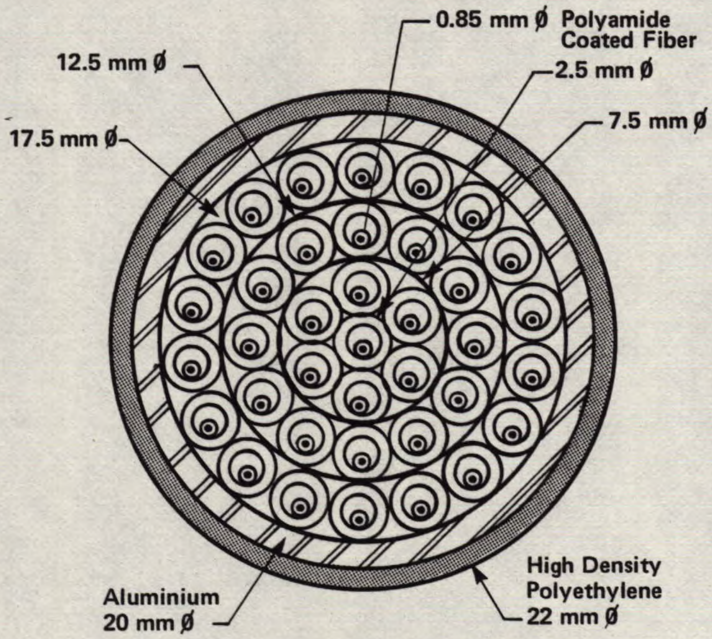


Figure 5.11 Fort (France) TIS LD 07 Cable



Prototype Cable (a)



Prototype Cable (b)

Figure 5.12 Cables De Lyon (France) Cables

6. SPLICES AND CONNECTORS

by J.F. Dalgleish

6.1 INTRODUCTION

Generally optical fiber transmission systems require two forms of optical fiber connection. A permanent fiber-to-fiber splice is needed to:

(a) join cable into lengths that exceed the maximum single length that can be handled in the field, and

(b) to provide a means of repairing damaged cable.

A detachable fiber-to-fiber connector is needed to:

(a) permit quick, reliable attachment of fibers to transmitters, receivers and amplifiers (i.e. repeaters), and

(b) to facilitate the rearrangement of fibers within a system.

6.2 SCOPE

It is generally agreed that intermediate and long length fiber optic transmission systems will employ low-loww, single fibers where each fiber in the cable is a separate transmission channel as opposed to fiber bundles in which a number of fibers carry the same signal. Consequently, this review deals exclusively with single fiber inter-connection technology. Most of the experimental hardware developed to date has been designed for use with multimode fibers (core diameters of 30 um to 100 um). One design approach has been aimed specifically at single mode fibers (core diameter approximately 2 um).

6.3 BASIC REQUIREMENTS FOR SPLICES AND CONNECTORS

6.3.1 Splices

6.3.1.1 Insertion Loss

The total splicing loss along a cable route must be substantially less than the total fiber loss. The objective in a system design will be to maximize amplifier (repeater) spacing by using very low-loss fibers. Splicing losses must, therefore, be minimized. An insertion loss of 0.5 dB per splice is currently considered to be a practical objective.

6.3.1.2 Field Installation

Traditionally with electrical systems, the value of a splicing technique has been judged largely by the ease and speed of operation in the field. It has been suggested that fibers might be prepared by splicing in the controlled environment of a work shop or factory and simply "plugged in" in the field - a concept commonly known as connector-ended cable.

The consequences of this approach are that:

a) cable lengths must be accurately predetermined,

b) provision for storage of slack cable must be made,

c) repair of damaged cable is not possible (i.e. cable must be replaced).

While some types of installations, such as inter-office telephone trunking, might be possible using connector-ended cable, as a general rule, it is desirable to avoid the above limitations and be able to perform the splicing operation completely in the field.

6.3.1.3 Mechanical and Environmental Stability

Spliced fibers must be as easy to handle as unspliced fibers and the splices must maintain their efficiency over an extended period of time (for example, telephone cable splices are designed for operational periods of up to 40 years). Many of the experimental fiber splicing techniques propose to use components such as plastics, resins and fluids which will have to be carefully selected and thoroughly tested to insure splicing stability.

6.3.2 Connectors

6.3.2.1 Insertion Loss

The insertion loss requirement for a connector is not as stringent as that of a splice because:

a) there are relatively fewer connectors than splices in a system,

b) an allowance must be made for remating characteristics and interchangeability.

The current goal of most companies appears to be a loss equal to or less than 1.0 dB per connector.

6.3.2.2 Repeatability

The design must be capable of repeated matings with little or no change in transmission characteristics.

6.3.2.3 Handling Characteristics

Optical fiber connectors must have handling and environmental characteristics similar to those of electrical connectors. Specifically:

a) the connector design must protect the fibers against accidental damage in the unmated condition,

b) the fiber ends should be accessible for cleaning in case the connector is contaminated,

c) greater versatility and system flexibility is possible if the connector can be installed in the field.

6.3.2.4 Suitability for Manufacturing

Before an experimental design can become available as a standard product at relatively low cost, it must be suitable for mass production.

Important characteristics include:

a) adaptability of design to various fiber geometries,

b) the number of close-tolerance part dimensions,

c) the ability of the manufacturing processes to hold the required tolerances,

d) interchangeability of parts.

6.4 SURVEY AND EVALUATION OF EXPERIMENTAL DESIGNS

6.4.1 General Comments

a) It is difficult to make direct comparisons between designs based on the reported insertion losses because of the number of variables involved. In addition to the basic ability of the hardware to accurately align fiber ends (i.e. control transverse and axial displacement and end separation), there are two other major influences - fiber quality and measurement technique. Variation in the outside diameter, core diameter and core/cladding eccentricity of the fibers used to test the splices and connectors, will contribute to the insertion losses. And, variations in the lengths of fibers used, type of fibers (graded or step index) and adjustments permitted during testing, also affect the losses.

Because there is no standardization of these variables, the reported losses can only be interpreted as indications of the potential of a design.

b) Compared to metallic systems, there are a large number of operations to be performed during splicing or the installation of a connector. The basic operations are:

   a) removing the protective coating on the fiber,

   b) preparing a smooth, flat surface on the end of the fiber,

   c) cleaning the prepared fibers,

   d) installing the fibers in the splice or connector hardware,

   e) retaining the fibers in place.

   Consequently, more equipment will be required than for metallic interconnections. In addition, because of the small size and the accurate alignment required, the equipment and techniques will be more sophisticated than that used for metallic interconnections.

c) The splices and connectors described and evaluated in the following sections are a selection of the experimental designs which hold the most promise for meeting the basic requirements outlined above. In some instances more than one group or organization has been developing the same basic design. In these cases, the most advanced development at time of writing has been referenced.

6.4.2 Splices

Refer to Table 6.1. Splices are presented in order of publication date.

6.4.3 Connectors

Refer to Table 6.2. Single fiber connectors and multiple fiber connectors are presented separately, each in order of publication date.

6.5 AVAILABILITY

6.5.1 All of the above designs of connectors and splices are being produced in limited quantities as experimental hardware for use with experimental systems. There are no standard, off-the-shelf single fiber (as opposed to bundles) connectors or splices generally available.

6.5.2 At time of writing, experimental connection hardware is being offered by:

a) Bell-Northern Research, Canada

Tentative specification sheets for single fiber connector and splice have been published and hardware is being offered as part of experimental systems using Bell-Northern Research plastic-coated fibers. Installation tooling is not available for sale.

b) ITT Cannon, USA

This company has indicated its intention to develop and market connector and installation tooling for use with ITT plastic clad fibers. No specifications yet available.

c) Furukawa Electric, Japan

Experimental preparation equipment (i.e. fiber breaking tool) is being offered for sale.

6.5.3 As indicated by the relative lack of availability and the incomplete data related to basic requirements, connection development is lagging behind cable development. A number of cables are offered for sale without an available, compatible connection technology.

6.5.4 Currently there is a greater demand for connectors than for splices as most of the experimental systems installed and under development are relatively short (less than 1 km) and consequently do not require cable lengths to be permanently joined.

6.5.5 Standard, off-the-shelf, connectors (and splices) and the associated installation tooling will become available as:

a) fiber and cable designs are standardized,

b) requirements are defined for specific types of applications.

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TABLE 6.1 SURVEY AND EVALUATION OF EXPERIMENTAL SPLICES

	Organization	Operating Principle	Insertion Loss Reported	Suitability for Field Installation	Mechanical and Environmental Stability	Figure No.	Refere No.
1.	Furukawa Electric, Japan	A close-fitting glass capillary is used to align prepared fiber ends. Fibers are held in place with epoxy.	0.3 dB average for 85 μm diameter step index core fibers.	Installed hardware is small in size and inexpensive. Tooling and handling techniques for inserting fibers and bonding require considerable skill.	No information provided. Splices have been installed in an experimental system.	-	1
2.	Bell-Northern Research, Canada	Prepared fiber ends are inserted into a pre-formed metal sleeve which has an alignment bore slightly larger than the fiber diameter. Splicing element is crimped into the fiber's plastic coating.	0.3 dB average for 125 μm diameter step index core fibers.	Installed hardware is small and relatively inexpensive. Tooling and procedures for installation do not require a high level of skill. No secondary operation to protect bare fibers is required.	Preliminary results indicate: a) tensile strength is equal to or better than fiber. b) little (<2%) signal variation with thermal cycling (-40°C to +60°C).	6.1	2
3.	Bell Telephone Labs, USA	Loose-tube splice. Prepared fiber ends are located in one corner of a square, glass sleeve and held in place with epoxy.	0.1 dB average for 68 μm diameter graded index core fibers.	Installed hardware is small in size and inexpensive. Tooling and handling techniques for inserting fibers and bonding require some skill. Additional protection for individual spliced fibers is required.	No information available.	6.2	3
4.	Corning Glass Works, USA.	Fiber ends are fused together using flame or electric arc.	0.3 dB average for 85 μm diameter core step index fibers.	Equipment and techniques best suited for use in factory for cable manufacture or repair. Some potential for field use. Protective coating must be placed over fused fibers.	Tensile strength of fused fibers approximately 60% of unfused fibers.	-	4
5.	Bell Telephone Labs, USA	"	0.1 dB average for 75 μm diameter core step index fibers.	"	Tensile strength not reported.	-	5
6.	Cables de Lyon, France	"	Typically 0.2 dB for 85 μm diameter core, step index fibers.	"	Tensile strength of fused fibers approximately 60% of unfused fibers.	-	6
7.	Bell Telephone Labs, USA	Mass splice for connecting fiber tapes has fibers bonded into a series of parallel Vee grooves. After polishing the ends, two identical halves are matched to form a splice.	0.1 dB average for 50 μm diameter core, graded index fibers.	Best suited for factory installation because of polishing and fixturing required to handle a large number of fibers simultaneously (i.e. connector - ended cable). Repair will be difficult.	No information provided.	6.3	7
8.	Siemens-AG, West Germany	Prepared fiber ends are aligned at the bottom of a formed Vee groove.	Approximately 0.2 dB for step index fibers. Core diameter not specified.	Appears to be readily suitable to field use. Tooling and techniques do not require a high level of skill. Installed hardware is inexpensive.	Preliminary results indicate no temperature coefficient over the range -20°C to 50°C.	6.4	8

TABLE 6.2 SURVEY AND EVALUATION OF EXPERIMENTAL CONNECTORS

	Organization	Operating Principle	Insertion Loss Reported	Repeatability	Handling Characteristics	Suitability for Manufacturing	Figure No.	Reference No.
		SINGLE FIBER CONNECTORS						
1.	AEG-Telefunken, West Germany	Fibers are bonded and polished in eccentrically mounted sleeves. One sleeve is rotated with respect to the other to bring fibers into alignment.	0.4 dB for 2 μm diameter step index core fibers (i.e. single mode) using an index matching fluid.	No information provided.	Requirement that signal be monitored during connection is not desirable for large core multimode fibres but is probably necessary for single mode fibers. Best suited for factory installation.	Good. Design adaptable to various fibers by changing only one dimension. Tolerances can be relatively loose because of adjustment during installation.	-	9.
2.	Fujitsu, Japan	Fibers are bonded in the center of precision machined metal sleeves. Two sleeves are aligned in a precision machined alignment tube. Fiber ends prepared by polishing.	1 dB average (No details of fiber used.)	±0.5 dB due to tolerance build-up. Design will not easily hold an index matching fluid.	Best suited for factory installation because of bonding and polishing. Fibers are well protected from accidental damage. Fiber ends are accessible for cleaning.	Poor. There are a large number of close tolerance dimensions including inside diameters. Design adaptable to various fibers by changing only one dimension.	6.5	10.
3.	Furukawa, Japan	"	0.7 dB using index matching fluid (No details of fiber used.)	±0.4 dB due to tolerance build-up. Design will not easily hold an index matching fluid.	"	"	-	11.
4.	Siemens-AG, West Germany	"	1 dB using an index matching fluid (No details of fiber.)	Not reported.	"	"	-	8.
5.	Bell-Northern Research, Canada	Preformed metal sleeve with a close fitting bore is used to align bare fiber ends. An index matching fluid is used.	1 dB average for 75 μm diameter graded index core fibers, using an index matching fluid.	Insertion loss variation less than 0.2 dB with repeated matings.	Can be installed in the field. Fibers are protected from accidental damage when the housings are unmated. Difficult to clean if alignment base is contaminated.	Good. Only a few parts. One close tolerance dimension can be accurately formed on a mandrel. Connector can be adapted to various fiber sizes by changing only one dimension.	6.6	12.
6.	Standard Telecommunications Labs, England	Watch jewel is used to center fibers in a metal ferrule. Fiber end prepared by polishing. Two prepared ferrules are located in a precision machined alignment sleeve.	3 dB average without an index matching fluid. (No details of fibers.)	Not reported but tolerance build-up can be expected to cause large variations.	Not well suited for field installation because of large number of parts and polishing. Fibers protected from accidental damage by ferrules and the fiber ends are accessible for cleaning.	Poor. There are a large number of close tolerance demensions and a relatively large number of parts. Selection of specific watch jewels for specific fiber sizes implies that matched assemblies are required.	6.7	13.
7.	Bell Telephone Labs, USA	Thermoset plastic plug is molded to the bare fiber. Two molded plugs put into an alignment socket to form a connector. Silicone index matching pads over the ends of the fibers reduce the reflection losses.	0.4 dB average for 55 μm diameter graded index core fibers using silicone index matching pads.	Loss variances of 0.1 dB to 0.3 dB.	Not suitable for field installation. Fibers are protected from accidental damage. Silicone pads are easily accessible for cleaning (or replacement).	Good. Molding conditions must be accurately controlled to maintain consistent plug dimensions. Fiber centering mechanism can accommodate various fiber geometries.	6.8	14.
8.	ITT Cannon, USA	Bare fibers are located at the center of three alignment rods.	Target: 1 dB but no experimental data provided. Design will not contain an index matching fluid.	No data provided but connector contains a number of moving parts which may wear.	Tooling is being developed for field installation, no details provided. Fibers are protected from accidental damage when unmated. Fibers may be difficult to clean if contaminated.	Fair. There are a relatively large number of parts, many with close tolerance dimensions. Adapting design to various fiber geometries could require dimensional changes on several parts.	6.9	15.

	MULTIPLE CONNECTORS						
9. Bell Telephone Labs, USA	The bared fibers at the end of a fiber ribbon or tape are potted in an encapsulating mold which precisely positions the fibers. The end of the encapsulated block is polished. Two blocks, prepared in the same mold, are mated to form a connector.	0.1 dB average for 80 μm diameter core fibers using an index matching fluid.	No information provided.	Best suited for factory installation because of molding and polishing operations. Mold structure should provide good protection to fiber ends. Fibers easily accessible for cleaning.	Fair. Molding conditions must be accurately controlled to maintain consistent dimensions. This will be more difficult than with single fibers. Design can easily accommodate various fiber sizes.	6.10	16.
10. AEG-Telefunken, West Germany	Bare fibers are bonded into Vee grooves in the circumference of a circular ceramic core and the ends are polished. Two prepared cores are aligned with an alignment cylinder in one Vee groove of each core.	Average greater than 1 dB using an index matching fluid.	0.5 dB to 2.0 dB due to misalignment caused by tolerance build-up.	Best suited for factory installation because of bonding and polishing operations. Fibers protected from accidental damage and ends accessible for cleaning.	Poor. Potential tolerance build-up would probably require matched assemblies which restricts interchangeability of connectors.	6.11	17.

Figure 6.1

Formed Splicing Element

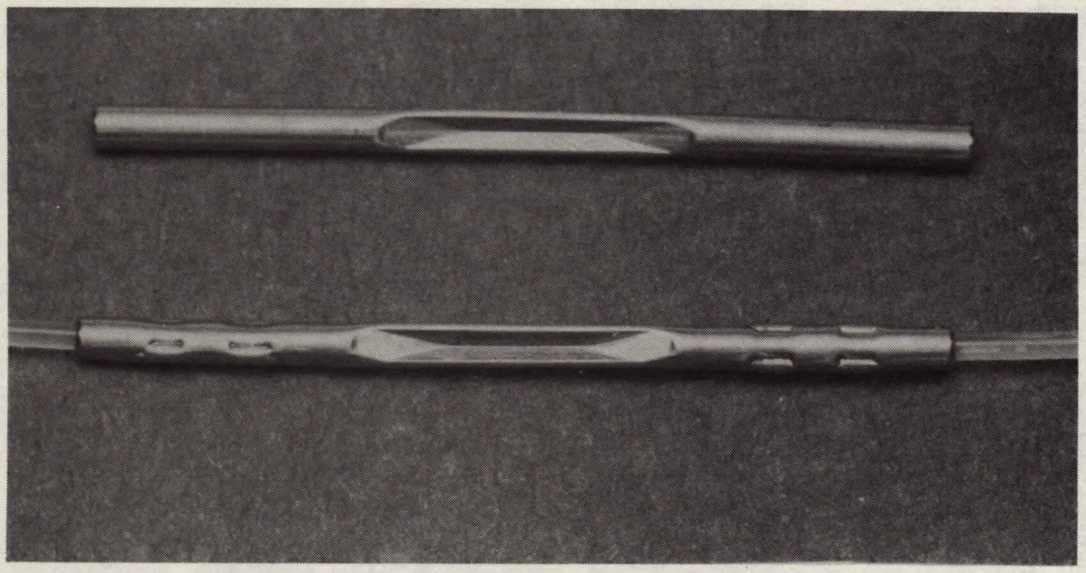


Figure 6.2

Loose—tube splice (BTL)

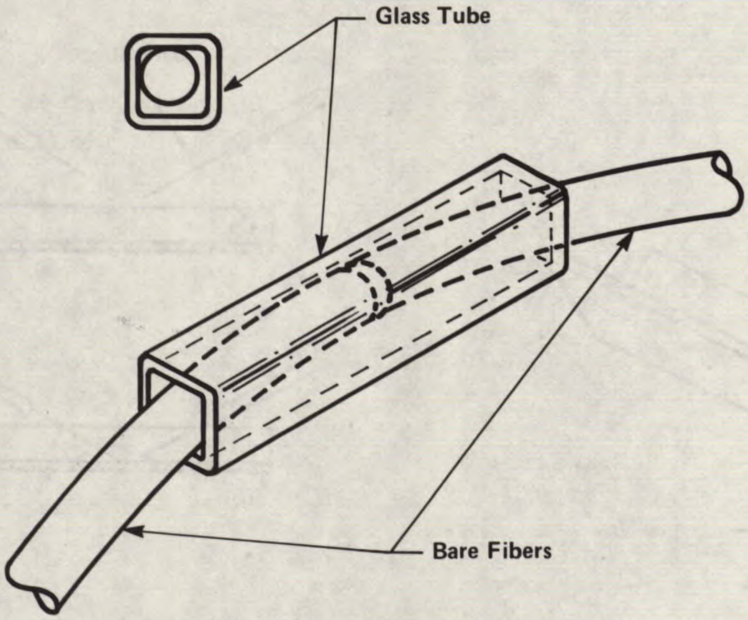


Figure 6.3

Mass splice (BTL)

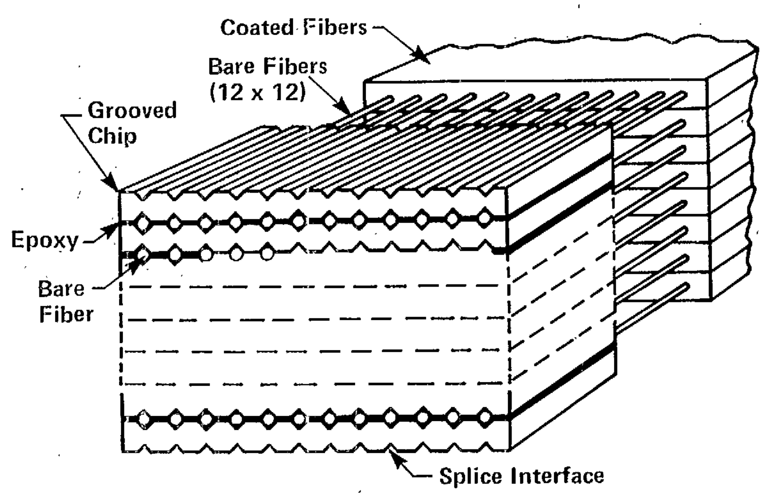


Figure 6.4

Vee groove splicing (Siemens AG)

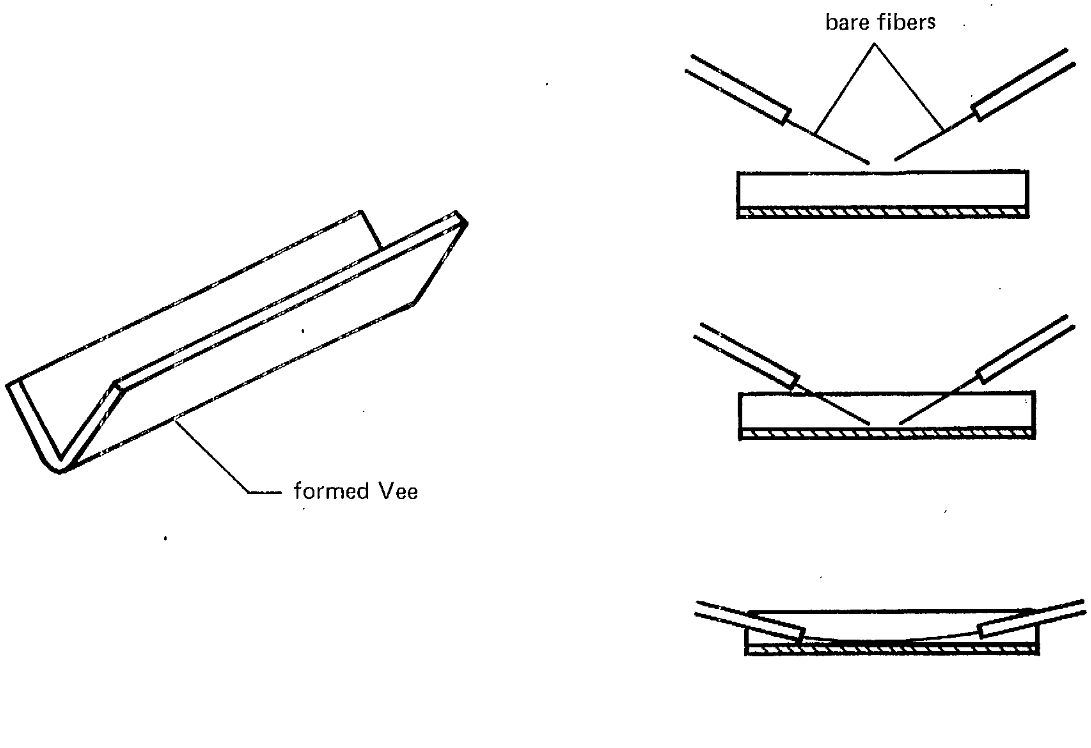


Figure 6.5

Concentric sleeve connector (Fujitsu)

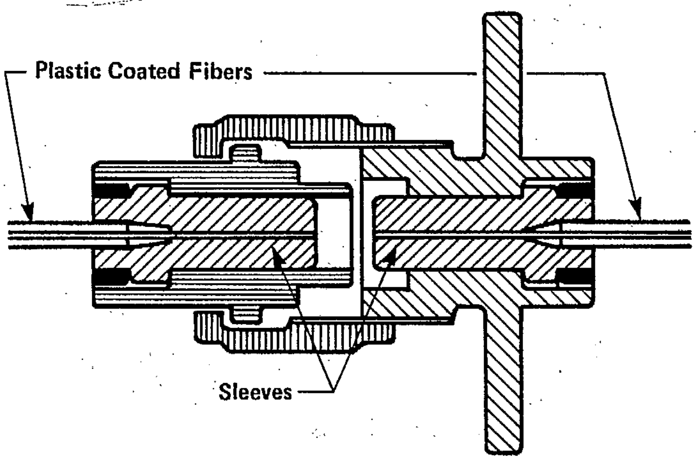


Figure 6.6

Formed element connector (BNR)

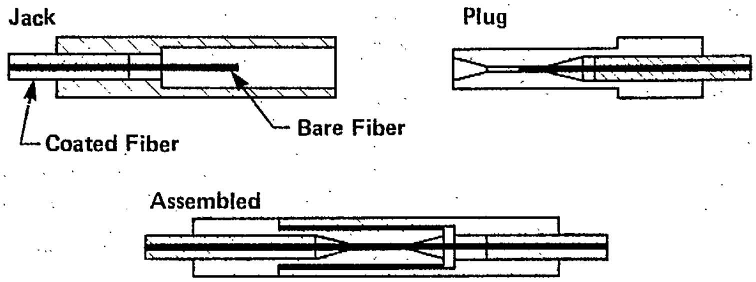


Figure 6.7

Watch jewel connector (ITT/UK)

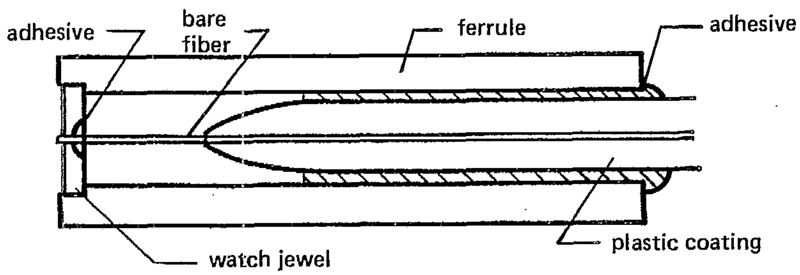


Figure 6.8

Molded single fiber connector (BTL)

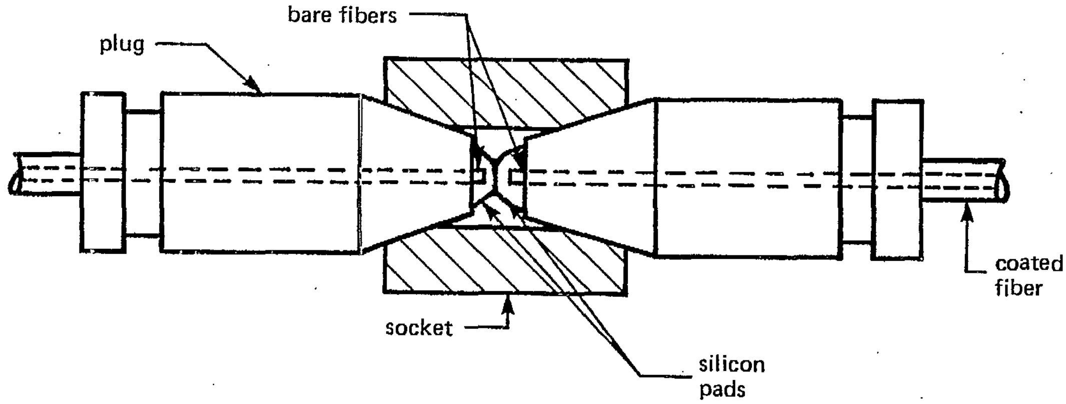


Figure 6.9

Three rod alignment connector (ITT Cannon)

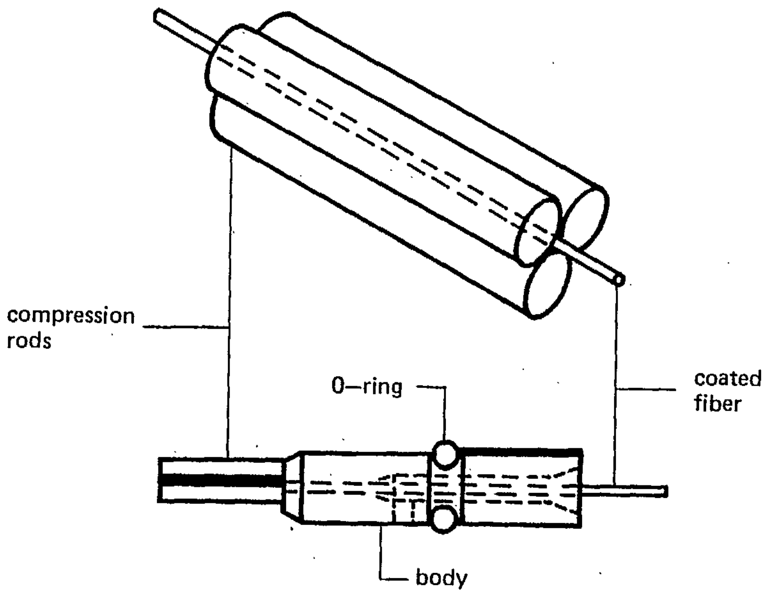


Figure 6.10

Molded multiple connector (BTL)

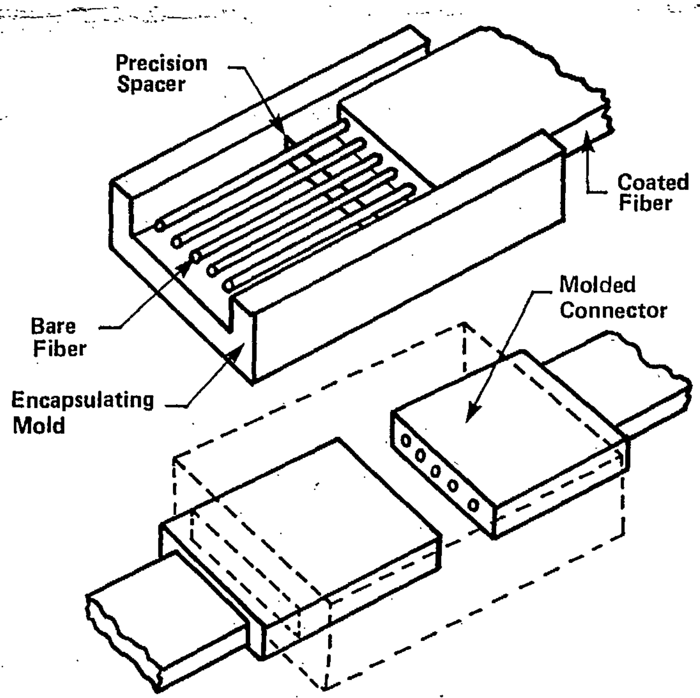
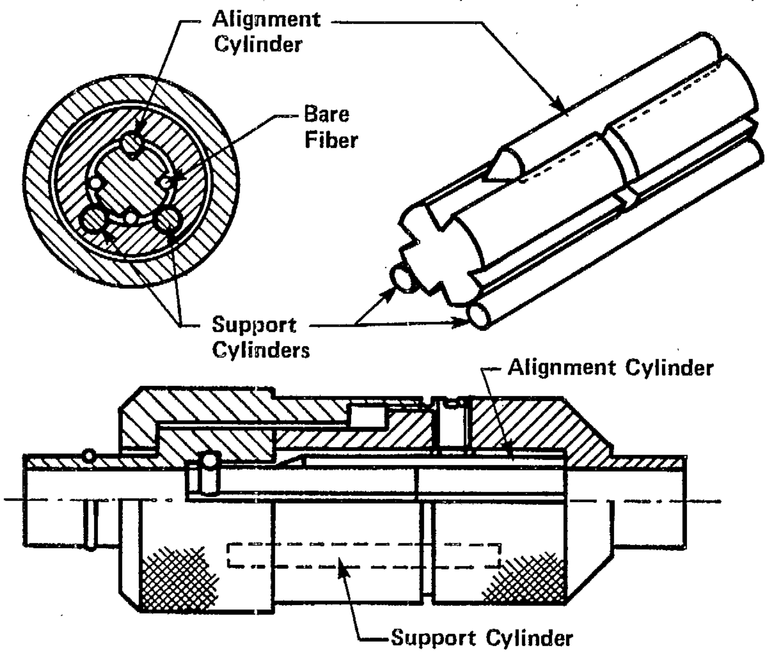


Figure 6.11

Multiple connector (AEG—Telefunken)



7. FIBER-OPTIC DIRECTIONAL COUPLERS - PART I

by M. Larose

7.1 INTRODUCTION

In an optical-fiber-based communication system, as in a conventional communication system, the signals carried by the transmission medium must often be distributed to or collected from a number of subscriber terminals. This signal distributing and/or collecting function can be accomplished with the use of directional couplers. In this section, the state-of-the-art of optical directional couplers will be reviewed.

Broadly speaking, optical directional couplers can be classified into two categories; namely a) the couplers designed to be used for fiber bundles and b) those for single fibers. Although the latter are of more interest for applications in this study, couplers of both categories will be reviewed, for completeness.

Functionally, directional couplers, both for fiber bundles and for single fibers, can be further divided into two types. First, "tee" couplers, which are used to branch out a fraction of the signal from the main communication path such as the trunk or feeder, and second, "star" couplers, which divided the signal into a number of equal parts. A star coupler is also referred to as a splitter. Both types of couplers may be used in communications networks, and which type is used in a specific case depends on the exact nature of the network.

7.2 DIRECTIONAL COUPLERS FOR FIBER BUNDLES

During the earlier days when fiber loss was high and power launching efficiency low, a common method used to improve the coupling transmission efficiency is to bundle a large number of fibers together, sometimes up to a few hundreds, to carry a single channel of information. This approach had the added attraction of redundancy, thereby gaining some protection against fiber breakage. Fiber bundles are still useful for short-distance communications, such as data busing on ships and airplanes, links between a computer and its peripheral terminals, etc.

Due to the relatively large cross-sectional area of a fiber bundle, the dimensional tolerances on associated system elements, including for example directional couplers, are less stringent in comparison to those of single fibers.

7.2.1 Tee Couplers

As mentioned before, a tee coupler is a device that taps a part of the light flowing in an optical fiber feeder. An "access tee coupler" is a coupler that performs the dual function of input and output in the trunk line. This dual function is essential to interactive communication systems. The coupler design will depend on whether the trunk line is operating in a uni- or bi-directional mode.

An early proposition for a tee coupler is shown in figure 7.1 It had the major drawback of requiring 3 mixer rods whose insertion losses are about 2 dB each. Thus, the first step toward the improvement of tee couplers was to reduce the number of mixer rods.

The Naval Electronics Laboratory Center (NELC) has reported uni-[1] and bi-directional[2] access tee couplers. The basic design for the uni-directional access coupler is illustrated in figure 7.2. The coupler consists of a glass block with an internal, fully reflecting mirror, mounted in a plastic holder. The mirror is oriented at an angle of 45° to the axis of the block, and extends only part of the way across. Some of the light entering the block from the main transmission line is reflected out the side, while the rest propagates through the block and into the next section of the trunk line. Light injected into the block from the side is reflected by the internal mirror and also enters the next section of the line.

The bi-directional coupler uses two fully reflecting mirrors at an angle of 45° with the block axis, and with their normals at 90° of each other. (See figure 7.3). The coupling ratio can be varied by tailoring the mirrors area.

For the uni-directional coupler, they have reported the following optical losses: 4.3 dB for throughput, 5.8 dB for input, and 6.7 dB for output. The last figure really represents the coupling ratio (=21%). Now if we evaluate the "excess insertion loss" which we define as -10 log (total useful output power/input power) we find it equal to 2.4 dB for the tapping function (from the trunk line to the photodiode). The insertion loss for the input function (from the LED to the trunk line) is still equal to 5.8 dB.

The "excess insertion losses" indicate the coupler quality better than the other terms, since they are really the measure of the useful optical power that has been lost in the coupling process.

For the bi-directional coupler, NELC have reported excess insertion losses ranging between 1.6 dB and 3.6 dB depending on the coupling factor chosen.

Milton and Lee from the Naval Research Laboratory have taken a different approach.[3,4] They have developed optical tee and multiple tee access couplers using bonded Pyrex rods. These are schematically represented in figure 7.4 and were intended for use in a uni-directional system, although the multiple tee in figure 7.4b) can be used in bi-directional systems.

These couplers have a central input and output section where bifurcation takes place and a scrambling or mixing section near the end to ensure that input light is evenly distributed over the output bundle. The coupling ratio can be adjusted by varying the relative area of the output arm, provided that there is good uniformity in the incoming light beam.

Milton and Lee have tested four devices, optical tee and multiple tee, which lengths were 38 and 76mm. The respective insertion losses are given in Table 7.1.

Longer devices had higher excess insertion losses, but the throughput beam uniformity was better. The excess insertion loss when the input was the trunk line did not vary significantly with changes in the numerical aperture of the input light beam. However, it was found that input through a bent Pyrex arm was very lossy at low numerical aperture, a 2 dB increase from NA = 0.45 to NA = 0.25.

This approach has the advantage of being able to couple light from a fiber bundle trunk line to another bundle, but insertion losses are still high. Moreover, if we consider the packing fraction loss encountered when re-entering the bundle, we have to add about 1.5 dB to the preceeding insertion loss figures. The last remark applies also to the NELC access tee couplers.

Researchers in Sperry Research Center came up with a new tee coupler design which did not involve a mixing or scrambling rod.[5] They use a distributive coupling technique in which some portion of the light is coupled in and out of all fibers of a bundle in parallel. The sheathing is removed from the fiber bundle over a length of a few centimeters, and the exposed fibers are arranged in a ribbon format lying cemented against a cylindrical surface of large radius. After polishing away the cladding on a short length of all of the fibers, a permanent optical contact is made between an external slab channel and the exposed core areas of all fibers. The slab uses taper elements on both sides to collimate light coupled out and to increase the efficiency for coupling light in. (See figure 7.5).

Sperry have also built a coupler using a non-tapered slab. They have measured a coupling ratio of 7.8% (-11.1 dB) and a radiative power loss (excess insertion loss) of less than 0.2 dB. For this non-optimal geometry, they have measured insertion loss into the fiber bundle from the side arm of 14.7 dB. Even with an optimal geometry, the insertion loss would remain relatively high ($\approx$ 11 dB).

However, the device has the lowest insertion loss for the tapping function reported so far. That could make it become attractive for systems having many terminals.

7.2.2 Star Couplers

Star Couplers are favoured for systems having many receiving ports because their insertion loss occurs only once. Thus star couplers can have somewhat higher insertion loss than tee couplers, and still be competitive.

Corning Glass Works has developed a star coupler[6-7] that uses a single mixer rod. The mixer rod is shown in figure 7.6 and the overall coupler is in figure 7.7. They have built 2 seven-port star couplers, one using bundles of 61 fibers, and the other bundles of 19 fibers. The average excess insertion loss, from one port to another port, was found to be 6.4 dB for the 61 fiber bundle star coupler, and 7.0 dB for the 19 fiber bundle one. The insertion loss does not vary much with the number of fibers in each bundle, and this could be extended to the number of terminals.

We could anticipate an improvement of 0.7 dB if an index matching fluid were used between the central bundle and the mixer rod. The 61 fibers per bundle unit has been successfully flight tested in an avionics package.

This completes the review of the different directional couplers suitable for fiber bundle communication systems. In general, they are not very sophisticated, but most of them have already been used in operational systems. They are primarily intended for data bus system, so great emphasis is placed on properties like bi-directionality and dual access to the trunk line.

7.3 SINGLE FIBER DIRECTIONAL COUPLER

Fiber bundles are interesting only for short systems (below 100 meters). For longer systems, single low-loss fibers are the best suited. So far for single fiber systems, the main effort has been given to point-to-point communication links. There has not been a great incentive toward developing practical directional couplers for single fiber, due in part to a lack of need in systems developed to date and in part to the difficulty of fabricating them because of the small fiber size. However, there have been some interesting experimental devices that have been realized in different laboratories. In this section, the most promising ones will be covered, with a brief description of their principle and their best achieved performances. For more details on particular devices, the interested reader should refer to the cited source.

7.3.1 Tee Coupler

We will begin with tees which only tap the signal in the fiber. We can classify these taps according to the interconnection performed: fiber-to-fiber coupling or fiber-to-detector coupling.

a) <u>fiber-to-fiber coupler</u>

These directional couplers can be realized by enhancing the mode coupling between two fibers by an appropriate perturbation. A tee coupler using two parallel tapered multimode fibers has been reported. The tapered section of the fiber converts higher order modes into radiation modes which are coupled in the other fiber. The throughput loss, power coupling ratio, and directivity were found to be 1.0, 10.2, and 20 dB respectively. From these figures, we can evaluate the excess insertion loss, as defined previously and it equals 0.5 dB. The coupling between two close fibers can also be increased by bending them, as shown in figure 7.8. For standard Corning Glass multimode step-index fibers, a 10 dB coupling ratio, a 21.6 dB directivity, and a 0.6 - 0.8 dB excess insertion loss have been claimed.[9]

Mode coupling between two multimode fibers can also be enhanced by bringing their cores sufficiently close to each other. This was achieved by welding two parallel silica fibers together with a CO_2 laser. For a device having an interaction length of 13 mm, a 11.8 dB coupling ratio and an excess insertion loss of 1.1 dB were reported.[31]

A simple directional coupler consisting of two closely parallel fibers loosely twisted together has been proposed.[10] It is intended for transmission line signal level monitoring applications. The coupling ratio being very low, 50 dB, the coupler has a negligible effect on the transmission properties of the line.

Another tee for multimode fibers that used two fused silica microprisms, has been reported[11]. (See figure 7.9.) The coupling ratio can be varied from 0 dB to 25 dB by coating an appropriate refraction film on the slanting surfaces of the two microprisms. The insertion loss could be as low as 0.6 dB.

b) Fiber-to-detector coupler

This kind of tee couples out the light in a fiber, and brings it to the surface of a detector.

A semi-transparent mirror-type directional coupler for multimode optical fibers[12] was built by cutting and polishing at a 45° angle two pieces of fiber, and afterward, inserting a dielectric film between the polished surfaces. The dielectric film mirror reflects out a portion of the light, perpendicularly to the fiber axis. Coupling ratios of 20 dB to 10 dB, depending on the refractive index of the dielectric film, excess insertion losses of .5 - .8 dB and directivity of 20 dB were measured.

Light can also be tapped out from fibers by removing the cladding at one point and embedding the fiber core in a low loss substance with a refractive index such that light is allowed to escape from the fiber core and can be directed towards a detector. Based on this principle, detector-taps were made[13] for multimode plastic clad fiber, (See figure 7.10), extracting as little as 2% (17 dB) of the light in the fiber, and with an excess insertion loss of less than 0.2 dB.

Another multimode fiber tap was constructed[14] by forming a suitable grating on the edge of a 100 um thick glass plate, which is pressed against the fiber, as shown in figure 11. The detector mounted on the opposite edge was able to detect 5.6% (-12.5 dB) of the light power in the fiber, and the excess insertion loss was measured to be 0.4% (.02 dB).

The characteristics and performance of these tee couplers are summarized in Table 7.2.

The preceding directional couplers have all been developed for multimode fibers. An interesting device[15] has been designed to extract a fraction of the light in a single mode optical fiber. It consists of a section of single mode fiber with the cladding removed on one side, a supporting silicon wafer with a preferentially etched groove, and a high index glass prism pressed against the semicylindrical fiber, as shown in figure 7.12. This particular device was rather lossy, but good coupling efficiency is reported to have been achieved.

Efficient access tee couplers for single fiber transmission line have not been extensively studied. However, one has been reported[16] that used a slightly tapered section of a multimode step index fiber. The principle and construction of the coupler is illustrated in figure 7.13. The coupler can be used efficiently only with a laser source.

7.3.2 Star Coupler

Splitters have been made either for single[17] or multimode[18] fibers. In the single mode fiber case, the power divider consists of a uniform main-fiber, as shown in figure 7.14. A 3 dB coupling was achieved with an excess insertion loss of 5 dB. This principle could be extended to produce a star coupler by positioning other sub-fibers around the main-fiber.

The splitter for multimode fibers was built using a CO_2 laser splicing technique and step index fibers. High coupling losses, i.e. 7-10 dB have been observed, but is seems that it could be reduced by using unclad graded index fibers.

A low insertion loss four-paired-port star coupler[19] has been fabricated. The coupler was assembled from biconical tapers of multimode fibers, and it is based on the same principle of the tee coupler of Ref. 8. The excess insertion loss through each branch of the coupler was found to be only 2.8 dB.

A type of star coupler that mixes and branches two incoming signals has been reported[20]. It uses Selfoc lenses and microprisms as illustrated in figure 7.15. The excess insertion loss was reported as less than 3.5 dB.

The preceding coupler performances and characteristics are summarixed in Table 7.3.

At the time of editing this report for publication, work at CRC, Ottawa, has yielded a directional coupler with a loss of only 0.1 dB[32].

7.3.3 Integrated Optics

Integrated optics devices always have been attractive for splitting or mixing guided light beams. The main difficulty with this approach is coupling the light from a fiber to a thin film optical waveguide. However, there have been some recent advances in this domain[21,22] which show that good coupling efficiency is possible for monomode fibers, and even for multimode fibers.

In general, the integrated optic directional couplers are based on three approaches: mode coupling, integrated branching network, field-induced channel waveguide.

Those based on mode coupling can be either passive or active devices. The simplest passive device consists of 2 parallel waveguides close to each other. With a new process using photolocking material , it has been possible to reduce the required coupling length to achieve 100% power transfer to 150 um. However, the device requires very accurate dimensional control to give good results.

A passive 3 dB coupler whose length does not require a precise control has been reported[24]. Actually, the maximum power transfer was 40% (-4 dB) and was limited by a fabrication problem, but still, good agreement with theory was observed.

There are some promising active directional couplers[25,26,27] of which the coupling ratios can be varied by applying a voltage on the electrodes placed on the surface of eletrooptic material. However, they are more intended for modulation applications than for fiber taps, although their electrically variable coupling ratio would be an interesting feature in a tee coupler system which could have to be extended (addition of new ports). It should be stressed that these directional couplers, active or passive, are efficient only in single mode operation.

An integrated branching network approach has been proposed[28] to perform splitting and tapping functions between fibers. It applies as well to multimode as to monomode fibers. The difficulty of fabricating 100 um thick waveguides has been overcome to permit the butt coupling of multimode fibers with the channel waveguides of the branching network. Results are not yet satisfactory for multimode fibers, but still they show great promise.

A simple thin-film beam splitter has been reported.[29] It is based on the partial reflection that occurs when a light beam encounters an optical perturbation. They used for perturbation a groove and a ridge in a thin guiding film as shown in figure 7.16

Finally, a three port multimode electro-optic directional coupler has been fabricated using electrodes to create field-induced channel waveguides in a thin plate of $LiNbO_3$. (See figure 7.17). The device required hundreds of volts to operate. The excess insertion loss was relatively high, (about 7 dB), but good switching performances were achieved, even for a white light source.

7.4 CONCLUSION

We have reviewed different directional couplers; the ones for fiber bundle systems are somewhat more mature devices than the ones intended for single fiber systems. However, fiber bundle systems are really limited to very short distances. Broadband communication systems will probably use only single fiber transmission lines. Appropriate directional couplers are still in the laboratory stage, though very interesting devices have been produced so far. (Table 7.2 and Table 7.3).

There is little doubt that integrated optics devices will be used as passive or active directional couplers, but it is likely that they will be introduced at a later stage.

We have seen that optical directional couplers have been, or could be produced in order to meet some specified functions and performances. At this point, we cannot determine which one(s) would be the best suited for a broadband communications network; this will be done in the following activities.

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TABLE 1 - EXCESS INSERTION LOSS (NA= 0.45)
FOR FIBER BUNDLE TEE COUPLER*

device length	38 mm	76 mm
Input from trunk line:		
Optical T	1.8 dB	2.5 dB
Multiple T	2.3 dB	2.6 dB
Input from input line:		
Optical T	3.8 dB	5.7 dB
Multiple T	5.6 dB	6.9 dB

*Figures in this table are obtained from Ref. 3

<u>TABLE 7.2 SINGLE FIBER TEE COUPLERS</u>

Category	Reference number	Figure number	Excess insertion loss dB	Coupling ratio dB	Directivity dB	Principle	Remarks
Fiber to fiber coupler	8	--	.5	10.2	20	mode coupling	-parallel tapered fibers -could yield a rugged device
	9	8	.6-.8	10	21.6	mode coupling	-bent fibers -difficulty in adjusting the coupling ratio
	31	-	1.1	11.8	---	mode coupling	-welded fibers -simple fabrication
	11	9	.6	0-25	---	partial reflection/transmission at a dielectric interface	-2 microprisms -fabrication difficult
Fiber to detector coupler *	12	-	.5-.8	10-20	20	partial reflection/transmission at a dielectric interface	-fibers cleaved at a 45° angle -fabrication difficult
	13	10	.2	?-17	--	evanescent field	-cladding removed
	14	11	.02	12.5	--	evanescent field	-grating opressed against the fiber -fabrication difficult

* These couplers require large area detectors which tend to be noisy.

TABLE 7.3 SINGLE FIBER STAR COUPLERS

Reference number	Number of ports	Excess Insertion loss dB	Principle	Remarks
17	2	5	taper coupling	-intended for monomode fibers -fabrication difficult
18	2	7-10	branching	-sophisticated splicing technique required
19	4-pairs	2.8	mode coupling	-parallel tapered fibers -could yield a rugged device
20	2 x 2	3.5	partial reflection transmission at a dielectric interface	-mixer function

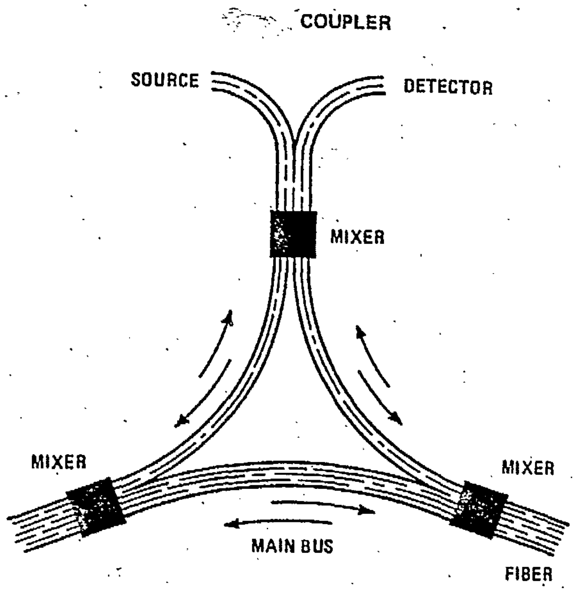


Fig. 7.1 Tee coupler using mixer rods.

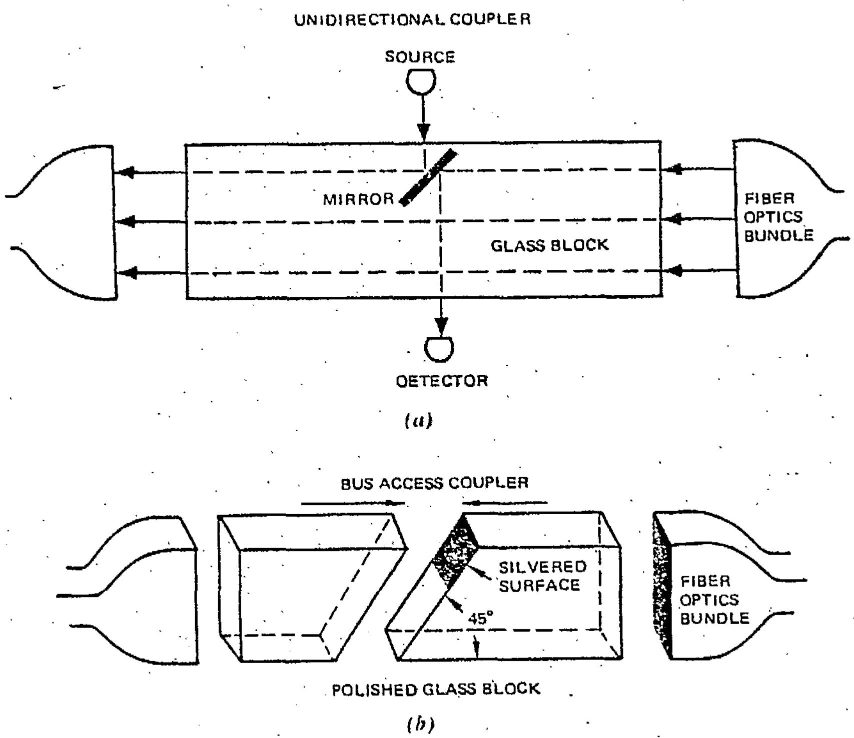


Fig. 7.2 NELC Unidirectional access coupler

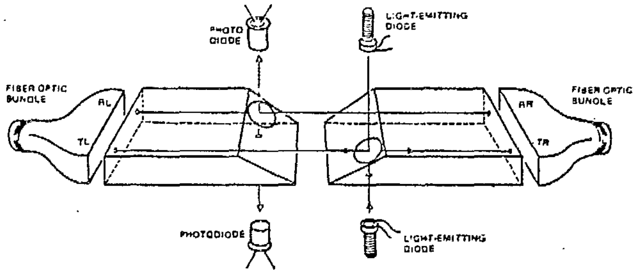
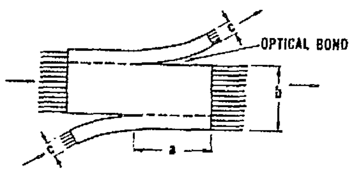
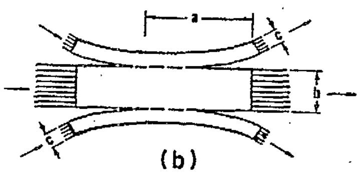


Fig. 7.3 NELC bi-directional coupler



(a)

OPTICAL T



(b)

MULTIPLE T

Fig. 7.4 NRL couplers

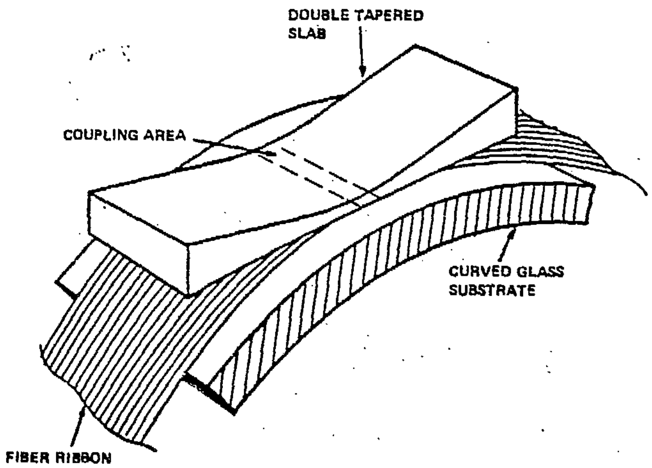


Fig. 7.5 Sperry tapered slab coupler

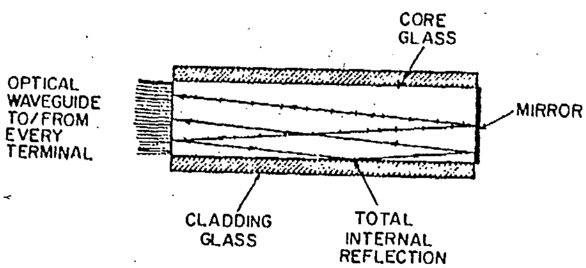


Fig. 7.6 Corning mixer rod

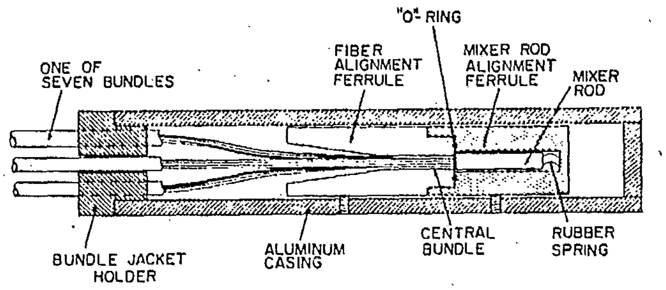
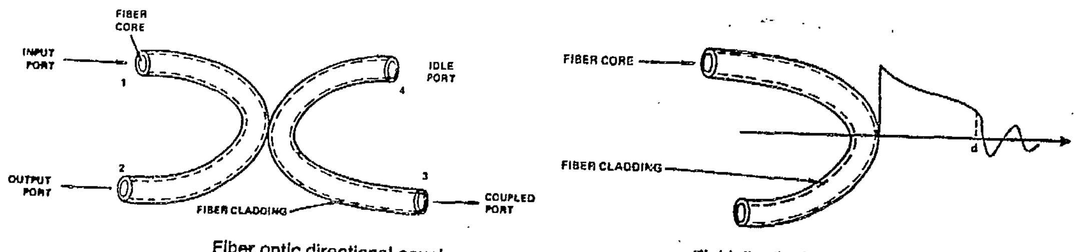


Fig. 7.7 Star coupler using Corning mixer rod



Fiber optic directional coupler.

Field distribution outside the bent optical fiber.

Fig. 7.8 Directional coupler using bent fibers

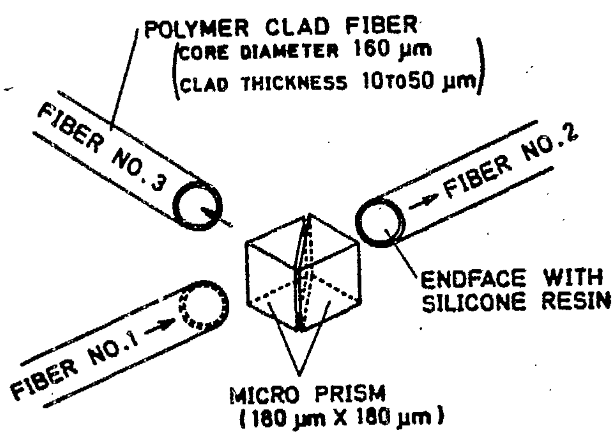


Fig. 7.9 Tee coupler using microprisms

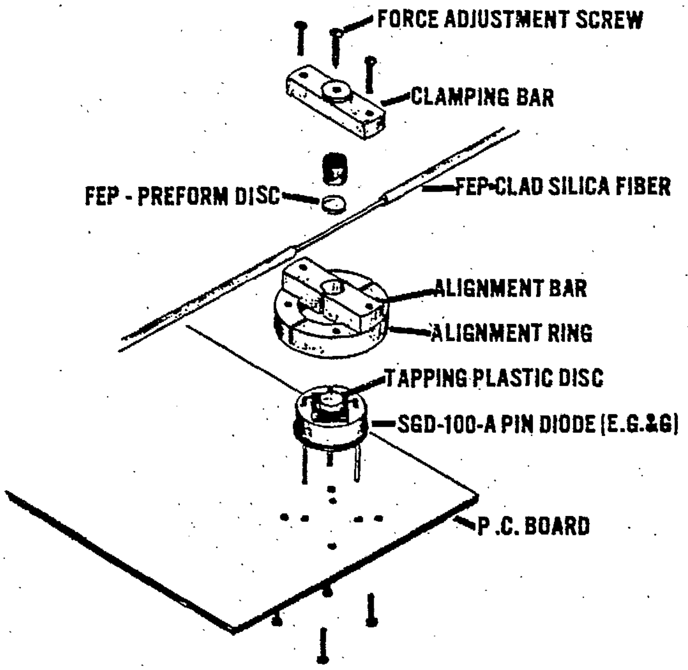


FIGURE 7.10
EXPLODED VIEW OF OPTICAL TAP

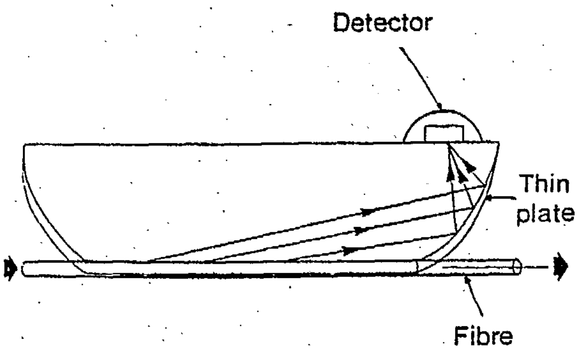


Fig. 7.11 Grating type optical tap

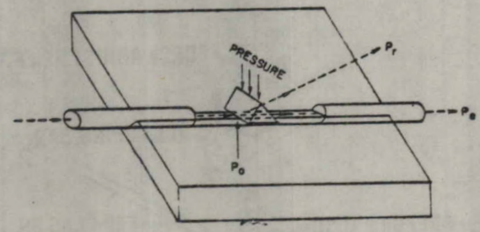


Fig. 7.12 Single mode coupler

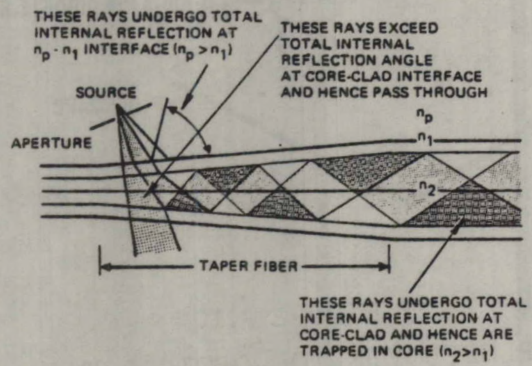


Fig. 7.13 Single fibre tapered tee coupler

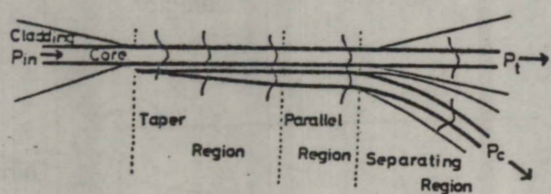
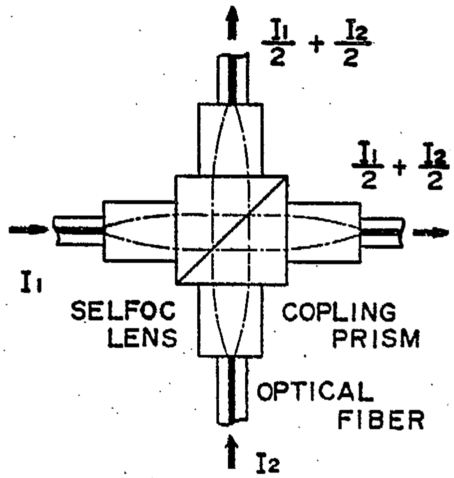


Fig. 7.14 Tapered fiber power divider



Optical coupler.

Fig. 7.15 Selfoc star coupler

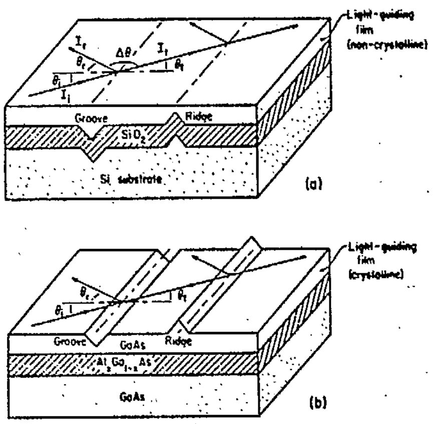
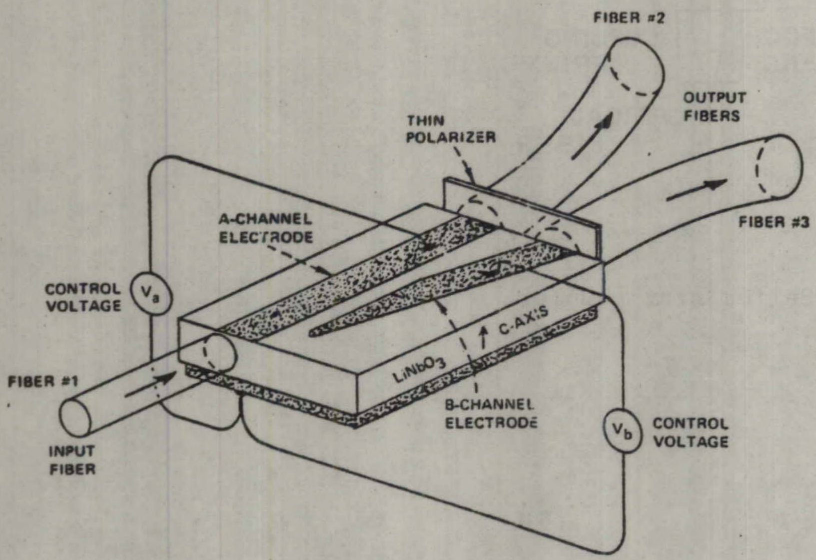


Fig. 7.16 Thin film beam-splitter



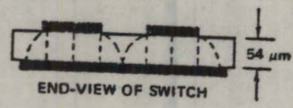


Fig. 7.17 3-Port electro-optic switch

8. FIBER OPTIC DIRECTIONAL COUPLERS - PART II

by T. Lukowski

8.1 INTRODUCTION

There are two general methods of interconnecting a number of data terminals with an optical fiber trunk line.

In a tee coupling system, branches from the main line are taken at various points. In the star-coupling system, all the splitting is done at a single optical component. Each of these methods has its own inherent advantages. In the former, it is possible to tap just a small part of the energy to monitor what is being transmitted. In the latter, transmission of a relatively uniform distribution of light from one input port to several output ports is possible.

Connector loss occurs at the ends of each tee. This is a major disadvantage of such a coupler. This contrasts with the star-coupler where only a single connector is required for each output. However, to feed the same number of outputs from a star, longer fiber links are required and fiber attenuation becomes important.

Attempts to create tee and star couplers have drawn from various fields of optics. At present, there are no such devices being marketed although papers and patents for a number of devices have been published.

8.2 PROPERTIES ASSOCIATED WITH DIRECTIONAL COUPLERS

There are many properties which determine the advantages and disadvantages of the various types of directional couplers:

1. Efficiency and Losses:

   Minimal losses at junctions between fibres and the coupler are desired.

   Scattering and Absorption should ultimately be independent of wavelength.

   Modes should couple equally without mode selectivity.

2. Fragility:

   It is desired that the device be insensitive to variations in ambient conditions.

   The device should be rugged.

3. Physical Size:

   The device should be small and yet large enough to work with in situ.

4. Structure:

A simple structure is desired.

Ease of manufacture and installation is a necessity.

5. Cost:

The device should be inexpensive to manufacutre, transport or install.

6. Reliability:

A lack of susceptibility to time - dependent fluctuations is needed.

A long lifetime is necessary.

8.3 TYPES OF DIRECTIONAL COUPLERS

8.3.1 Couplers Using Fibers

Of the many proposed couplers, the one which presently is most promising is one in which two fibres are placed side by side and light travelling in one is coupled into the other.

In one embodiment, two multimode fibers are twisted together with index matching fluid filling the coupling region between them (Fig. 8.1a). Only a small amount of power can be extracted from the main transmission line, and this is not uniformly distributed among the various modes (1).

Another mode selective coupler involves placing two fibers side by side bent to a radius such that some guided modes in one fiber become radiating ones (Fig. 8.1b) (2). To do so, the fibers are bent and their claddings etched off. One disadvantage of this method is the fact that higher order modes are removed at the first coupler so that sharper and sharper bends are required to strip off lower order modes at each successive tee.

Greater transfer efficiency can be achieved through the use of biconical tapered fibers placed side by side (Fig. 8.1c) (3) (4). Use of two such fibers creates a tee coupler. Higher order modes propagating in the incident arm of the coupler have cutoff points in the decreasing taper. These become radiation modes trapped by the higher refractive index of the surrounding adhesive and then guided to the region of expanding tapered sections. Here the radiated power reconverts into guided modes approximately equally into all fibers other than the original fiber which still propagates low order modes. With selective high order mode launching, a 3 dB coupler has been realized. All tapers are created by elongation of a heated section of the fiber (pulling).

A similar device using etched tapers has been found to give a high coupling efficiency, though, with multimode fibers this is again a mode selective device (5). Other geometries include the formation of a "T" with a tapered fiber as each arm and the use of a tapered branch attached to the non-tapered "main stem" (fig. 8.1d).

One of the difficulties with tapered couplers lies in maintaining the close tolerances necessary for a uniform taper of desired dimensions.

A main advantage is the possibility of using such couplers for monomode fibers.

Fusion of three pieces of fiber with a CO laser has produced a tee coupler (Fig. 8.1e) (6). Using micropositioners to hold the fibers in place, the laser is used to melt the glass.

Another coupler has been conceived wherein two fibers are crossed. Removal of the claddings at their intersection leads to coupling (Fig. 8.1f) (2).

8.3.2 Planar Couplers

Many ideas have been proposed for the use of planar branching waveguides on substrates. In one of these, a higher index strip waveguide pattern is formed on a quartz substrate by using standard lithographic processes (Fig. 8.2a) (7)(8). Losses occur as the scattering due to surface roughness and at the bifurcations on the substrate.

Another class of planar couplers involves waveguides side by side on a substrate with overlap of evanescent fields resulting in energy exchange between them (Fig. 8.2b). Since penetration depths are of the order of a few hundred nanometers, for reasonable coupling lengths, the waveguides must be brought close together. This is a manufacturing difficulty.

One such example involves parallel channel guides embedded at the surface of GaAs via proton bombardment (9). Light input into one channel flows into neighbouring ones via coupling of evanescent modes.

In another method three waveguides are used with the central one of a different guide index than the others (10). A thin dielectric film of slightly lower refractive index than any waveguide cores is used to achieve coupling - its thickness controlling the coupling strength.

Both of the above methods offer the advantages of controlling the amount of light transferred between channels by the choice of the separation of waveguides, the coupling length or the type of dielectric material between them.

In all planar - type couplers there are losses at the butt joints between the fibers and the planar guides.

8.3.3 Grating Couplers

A radical departure from previously attempted configurations is one using a periodic deformation of the fiber produced by pressing it between two mechanically manufactured aluminum gratings (Fig. 8.3a) (11). This induces coupling between guided and radiated modes and enhances tunnelling of power transfer to radiated modes into a higher index medium. Its geometry is so designed to focus the light beam onto the external photodetector, as with a semi-spherical ball. Variation of grating spacing can be used to favour coupling of certain modes.

The same effect is obtained by pressing the fibre in contact with an amplitude grating of plate glass (Fig. 8.3b)(12). These plates transparent to the radiation are so shaped that the emerging radiation is focussed to a point on the edge away from grating.

A big advantage of these methods is the ability to vary the amount of coupling, and to release the deformation when coupling is no longer desirable.

8.3.4 Scramble Couplers

Various methods have been proposed using glass scramblers as star couplers. One of these demands an elongated conically shaped rod having parallel endfaces (Fig. 8.4a) (13). At the smaller end is the termination of a single fiber whereas at the other end numerous fibers are butted. The outer surfaces of the taper reflect light back into the rod.

A similar method involves a glass cylinder surrounded by lower index cladding with all fibers butted against one end face of the rod (Fig. 8.4b) (14). The other end is faced with a mirror. One of these fibers is used as the input and the others as the output.

In another star coupler, radiation from the multimode fiber is directed through a large diameter Selfoc lens which scrambles the radiation uniformly over its entire output face (Fig. 8.4c) (15). This face contacts the input ends of smaller diameter Selfoc lenses each of which focuses the scrambled light to a single optical fiber. Several inputs can be mixed to give several outputs.

A packing fraction loss is common to all scramble couplers due to the area occupied by fiber claddings and interstices.

8.3.5 Holographic Couplers

The principle of holography has been utilized in a group of optical couplers. These include the coupler which can couple one fiber into several fibers of the same or different cross section (Fig. 8.5) (16). A high resolution photographic plate with a holographic pattern is used as the light divider by focussing the input light into several outputs. Such a method involves critical tolerances in lining up fibers and the holographic plate.

8.3.6 Lens and Mirror Couplers

One such coupler (17) utilizes a lens to expand and collimate the output light from a single fiber (Fig. 8.6a). A mirror placed at a 45 degree angle to the axis of the optical path is used to couple out a fraction of the radiation. A second lens is used to refocus the light for further transmission in the fiber.

In another method, a semi-transparent mirror is created by cutting and polishing two pieces of fiber at a 45 degree angle (Fig. 8.6b) (18). A dielectric oil (e.g., H O, silicon-oil, CH I) is inserted between the polished surfaces.

Other schemes (19)(20)(21) utilize transparent members with planar surfaces arranged in various configurations such that transmission and reflection occur at each interface (Fig. 8.6c). In one of these arrangements, the ratio of throughput light to tapped light can be varied. These tend to be fairly complicated and involve exact tolerances on the glass pieces and the methods of support to keep them in the desired configurations.

8.3.7 Prism Coupler

A prism may be used to tap light. A section of the fiber cladding and possibly core is removed and the resulting fiber has a high index glass prism pressed against it (Fig. 8.7a) (22). Evanescent or direct coupling from the fiber into the prism occurs. The method can be used for both multimode and monomode guides. The depth to which the cladding (or core) is removed determines the power pickoff ratio.

Two microprisms of fused silica stuck together back to back by silicone resin have been successfully used as a directional coupler (Fig. 8.7b) (23). One input fiber and two output ones lead to three of the four rectangular faces. A major advantage of this method rests in the possibility of transferring all modes, i.e., a lack of modal selectivity. For this reason, though this method demands critical positioning, it may be most desirable. A difficulty arises due to light scattering within the coupler.

8.4 CONCLUSION

It is clear that there are many possibilities for directional coupling. Each of these has advantages and disadvantages.

A table of properties of those couplers for which data is available is given. For the experimental conditions it is necessary to refer to the original papers.

Based on the above possibilities, the use of the tapered fibers (by pulling) is expected to be the best available at the present time. This requires the least complicated fabrication and tends to offer efficient coupling. Unfortunately, this occurs at the expense of mode selectivity. A coupler lacking mode selectivity may be fabricated as the microprism type. This will be, however, at the expense of a more complicated manufacturing process.

Judging by recent trends, there may be new and still better couplers appearing soon for research and development work is now being carried on in laboratories around the world.

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TABLE 8.1 Properties of Selected Couplers (Approximate Values)

COUPLER (at .633µ)	INSERTION LOSS $\left(1-\frac{\text{TOTAL POWER OUT}}{\text{TOTAL POWER IN}}\right)$	POWER TRANSFERRED TO THIRD FIBRE	MODAL SELECTIVITY
Side by Side Fibers (Pan) 2	13 to 17%		Higher order modes transferred
Tapered Coupler (pulled) (Ozeki et al) 3	33%	4.6%	Higher order modes transferred
Branch Tapered Coupler (etched) (Yamamoto et al) 5	32%	50%	Values for single mode coupler
Aluminum Grating (Jeunhomme et al) 12	32% 2%	50% 10%	Multimode tend to favour higher order modes, but lower may couple out
Glass Grating (Stewart et al) 11	.4%	5.6%	
Microprism (Suzuki et al) 23	13%	from .32 to 100%	Multimode non-selective

Note: Many of these values are from preliminary reports on the devices tested. Other devices not included due to lack of satisfactory data

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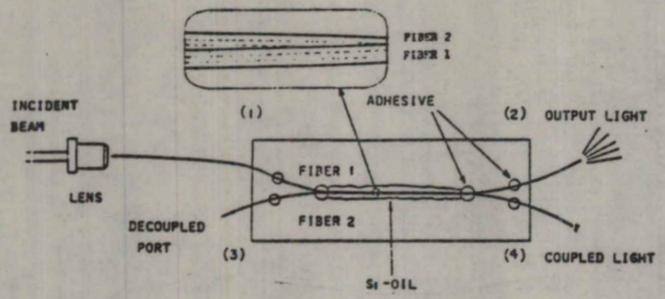


Fig8.1a: Multimode Fibers Twisted Together[1]

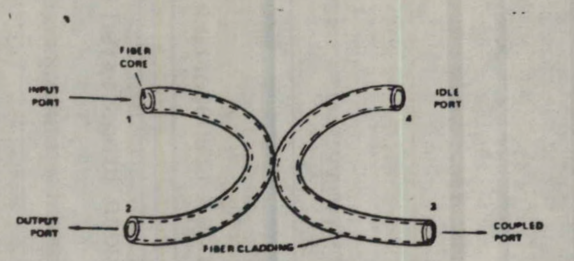
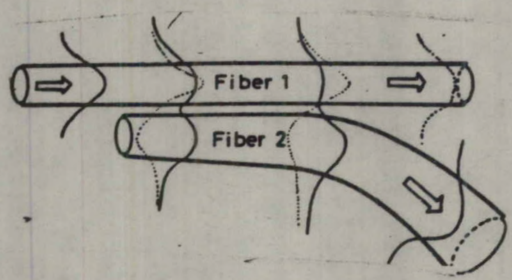


Fig8.1b: Bringing Cores of Fibers Close Together[2]

Fig8.1c: Biconical Tapers Side by Side[3]



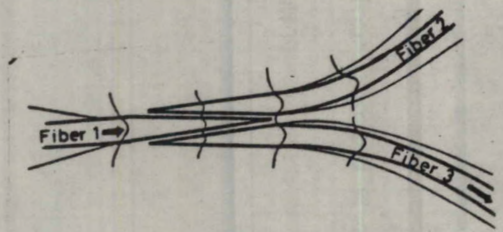


Fig.8.1d: Two possible Juxtapositions of Tapers[5]

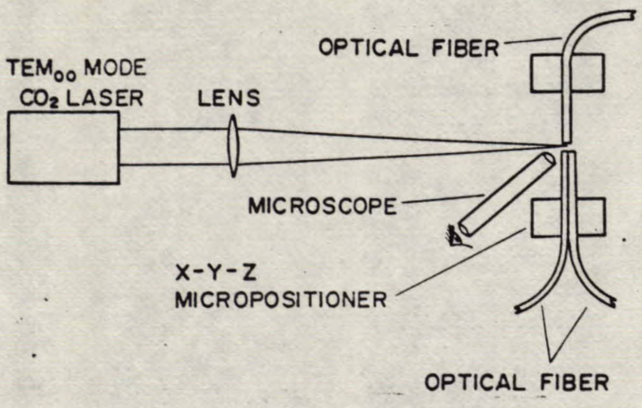


Fig.81e: Fusion of Fibers to Make a Coupler[6]

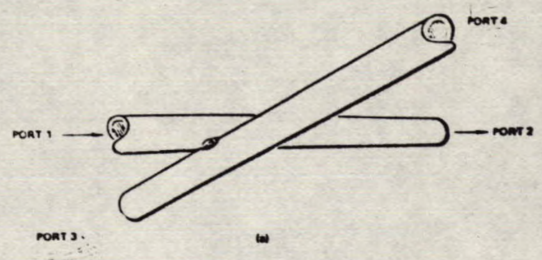


Fig.8.1f: Crossed Fibers[2]

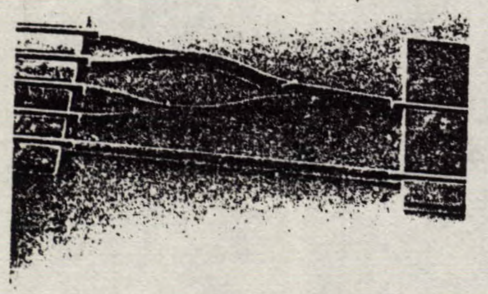


Fig.8.2a: Planar Branching Waveguide[7]

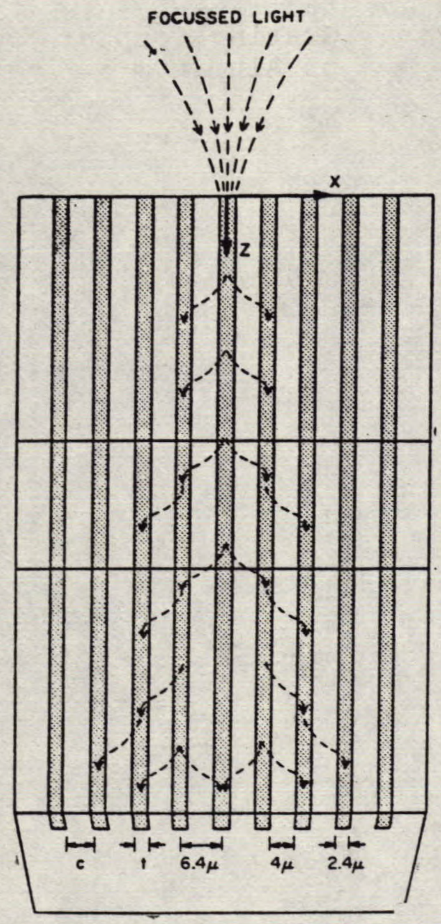


Fig.8.2b: Channel Optical Waveguide Directional Coupler[9]

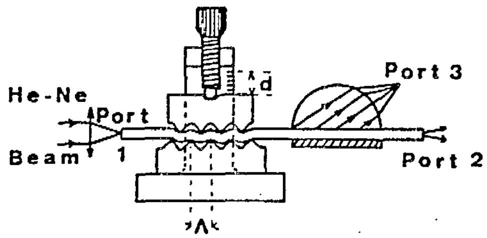


Fig.8.3a: Grating Coupler of Aluminum[11]

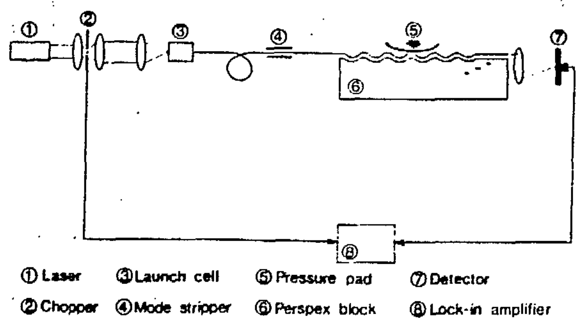


Fig 8.3b: Grating Coupler of Glass[12]

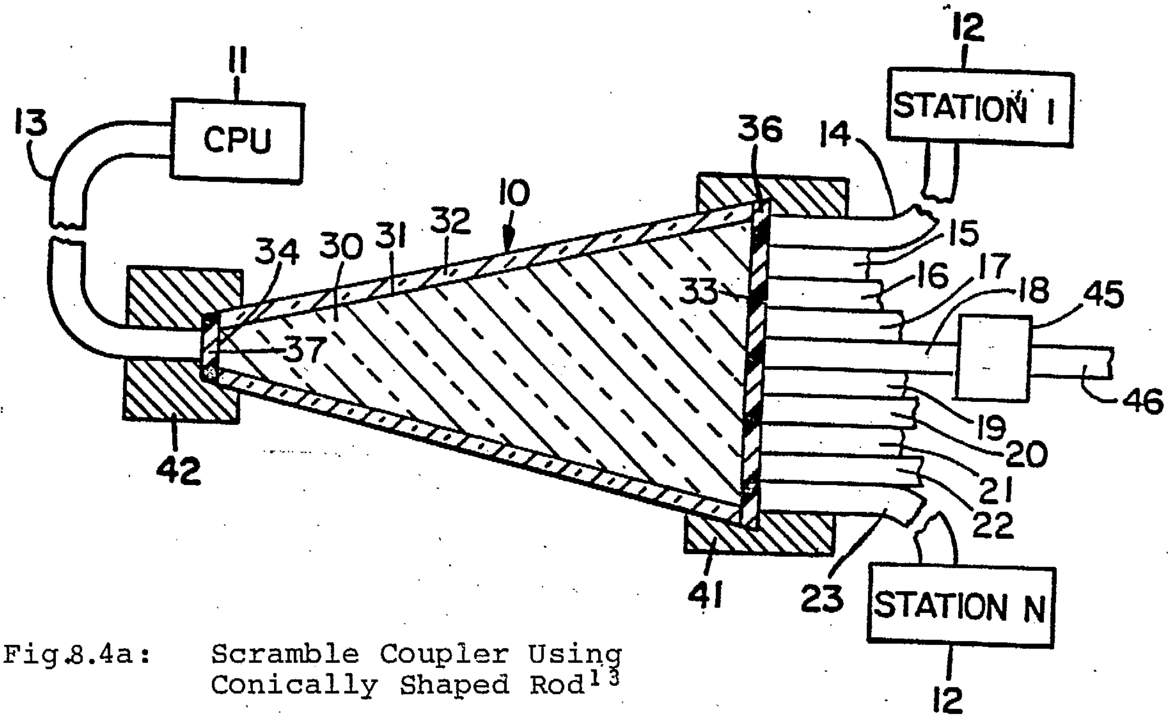


Fig.8.4a: Scramble Coupler Using Conically Shaped Rod[13]

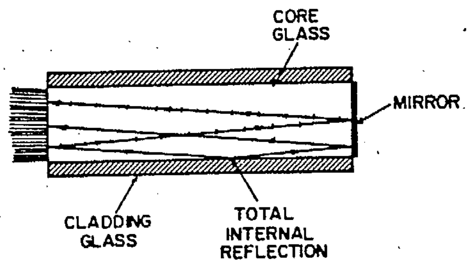


Fig8.4b: Scramble Coupler Using Glass Cylinder[14]

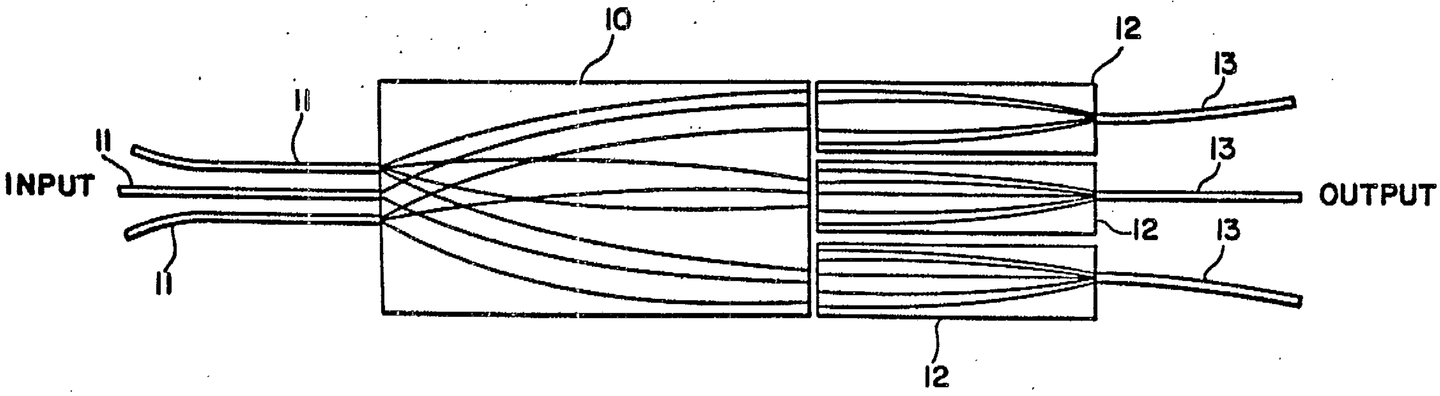


Fig.8.4c: Star Coupler Using Selfoc lens[15]

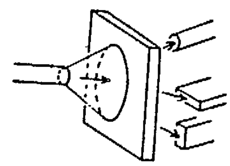


Fig.8.5: Holographic Coupler[16]

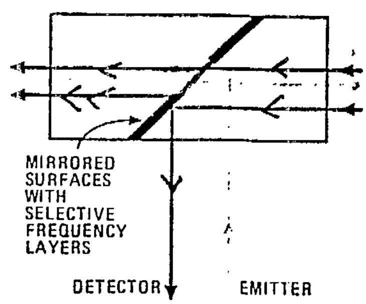


Fig.8.6a: Reflecting Mirror Coupler[17]

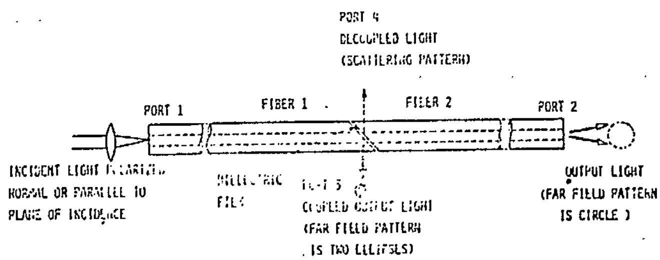


Fig.8.6b: Semitransparent Mirror Coupler[18]

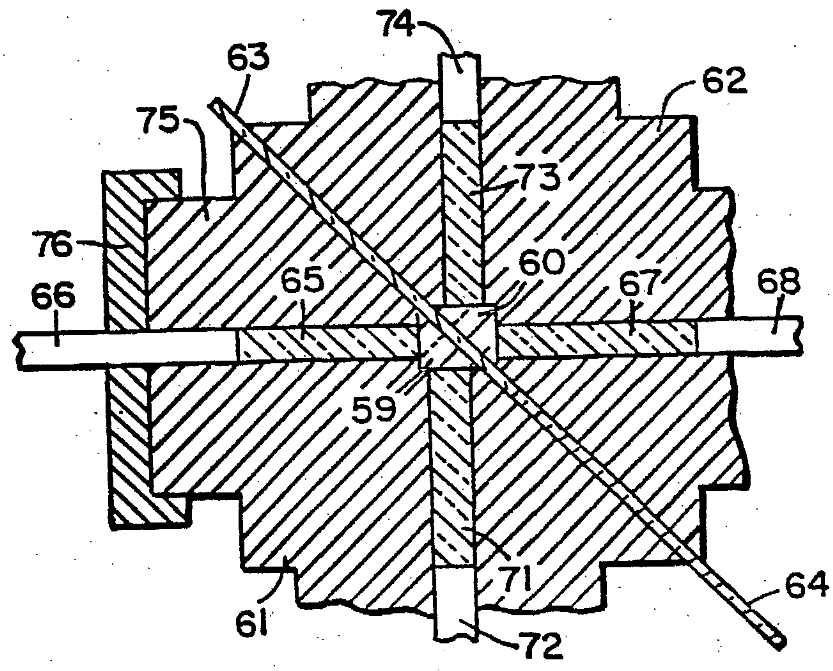


Fig.8.6c: Transparent Members Used to Couple Light[21]

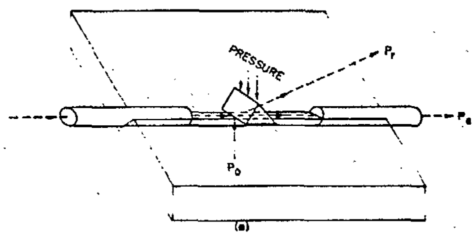


Fig.8.7a: Prism Coupler[22]

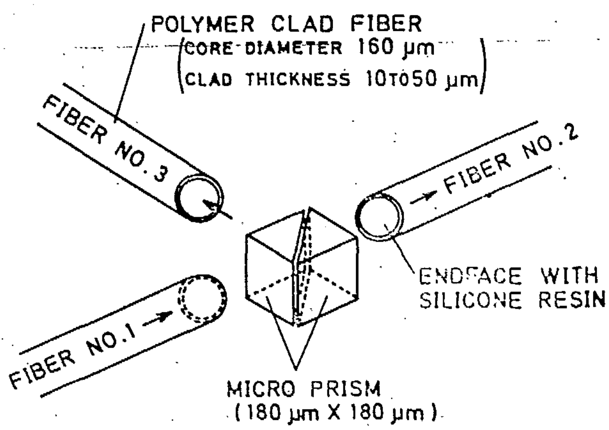


Fig.8.7b: Microprism Coupler[23]

9. ELECTRO-OPTIC TERMINALS AND REPEATERS

by T. Witkowicz

9.0 INTRODUCTION

Electro-optic terminals can be evaluated by considering the performance in two areas, the optical source or transmitter and the photodetector or a receiver. The electronic circuitry associated with the terminals are a driving circuit for the source and the amplifier circuit for the photodetector.

The driving circuitry is normally quite simple, often consisting of an emitter coupled pair for data transmission and a power transistor for analogue. High current capability (typically 1A max. current) may be required depending on the application. In data application the electro-optic device is usually prebiased (small current flows trough the device when it is in the "off" position) in order to achieve faster rise-time.

In cases where linearization techniques are employed a more sophisticated circuitry is in order.

Owing to the fact that the photodetector is a current source, which converts optical signal into electrical current, high input impedance amplifiers are used to achieve a best signal to noise ration.

The following is a brief characterization of the state of the art terminals and systems. The systems described either have already been built (at BNR or elsewhere) or will be made available in the very near future. Only the electronic circuits directly associated with the electro-optic devices are described here, with the understanding that the rest of the circuits (such as amplifiers, comparators etc) are conventional.

9.1 ANALOGUE APPLICATIONS

The criteria defining an analogue optical transmission system are, a signal to noise ratio (S/N) available light power and linearity of the source and the detector. The S/N at the receiver is defined as a ratio of a p-p received signal level to the rms noise level. Depending on the type of detector used the noise may be due to the average signal current fluctuations (shot noise) as in the case of the avalanche photodetector (APD) or a combination of thermal, shot and the amplifier noise as in the case of PIN detector.

A choice of the detector is mainly made on the basis of the bandwidth requirement with the PIN detector being used for bandwidths less than 5 MHz and an APD for higher bandwidths. The harmonic distortions of the detectors are more than 60 dB below the fundamental. The amplifying stage contains normally a high input impedance (low input capacitance) low noise amplifier. Field effect transistors are best suited for bandwidths below 50 MHz and bipolar transistors for higher bandwidths. There are two commercially available (1) hybrid photodetector-amplifier modules. The amplifier characteristics are as follows; bandwidth (3 dB) 40 MHz, input capacitance 1 pF and an equivalent noise voltage of 1.5×10^{-8} V/ Hz. The required average received light power to obtain a S/N of 40 dB is -62 dBW and that for S/N of 56 dB is -48 dBW.

It has been reported by BNR (2) that by using the neutralization techniques the input capacitance of 0.15 pF may be obtained with corresponding sensitivities of -68 and -58 dBW respectively. With source linearity as a serious constraint the light emitting diode (LED) is at present the best overall choice for the analogue applications. A recently reported (3) linearization technique allows a 2nd harmonic suppression to -60 dB below the fundamental, at 75% modulation depth. The average light power coupled into the fibre (N.A. = 0.22) from the linearized diode is approximately -10 dBm.

Presently available systems (4) have a typical link loss of 25 dB (S/N = 55 dB, diff. phase 0.2° and diff. gain of 0.3 dB).

The cross modulation at useful light power levels has been a limiting factor on the number of channels that can be transmitted by a single system, limiting the number to 3 (5) however, this situation will change as linearized LED's become readily available.

9.2 Digital applications

Owing to the fact that the light signal is unipolar (i.e., either "on" or "off"), the data format must normally be converted from a standard bipolar to a binary format. In order to provide sufficient timing informatin and a possibility of error monitoring the binary is then converted into a 2-level code containing more transitions and some redundancy. Normally used codes are 2B3B and 2-level AMI.

The performance of digital transmission terminals is mainly defined by the available output light power at the transmitter end, and the sensitivity of the receiver (i.e. necessary peak light power to maintain an error rate of 10^{-7}). The laser diodes (LD's) are seen as a prime choice for applications in digital fibre optic transmission systems, despite the fact that at present the laser lifetimes are shorter than the lifetimes of LED's.

Avalanche photodetectors are commonly used as receivers in medium and high capacity systems, while PIN detectors are used at low bit rates. The sensitivity of the receiver is determined by the amplifier noise power and the detector noise as in the case of an APD. As in the case of analogue receivers the best S/N is obtained for highest possible amplifier input impedance (limited by the corresponding input capacitance).

9.2.1 Available performance for receivers at DS-1, DS-1C and DS-2 rates.

Two types of photodetectors are used for these rates. The PIN detector is used in conjunction with an integrating low noise (FET) amplifier, followed by an equalizer compensating for the narrow-band front end. Typical bandwidths of the front end are of the order of 10-20 KHz.

Reported (6,7) sensitivities for such systems are:

DS-1	-54 dBm
DS-1C	-51 dBm
DS-2	-49 dBm

A more complex repeater design is required if an APD diode is to be used in the system (e.g., gain of an APD needs to be stabilized against temperature variations).

The corresponding sensitivities are -67 dBm, -65 dBm and -62 dBm respectively (7).

At the present time very few systems are available off the shelf and most requirements are met by custom made systems.

The CIT ALCATEL Laboratories (France) have systems available at 2, and 8 Mb/sec with sensitivities of -53 dBm and -43 dBm respectively. Both use LED's as sources with peak power coupled into the fibre equal -10 dBm.

A system at 7.8 Mb/sec available from Nippon Electric uses a laser source (3 dBm peak power) and an APD with a sensitivity of -50 dBm.

9.2.2 Data transmission at high bit rates.

In the high capacity fibre optic systems, it is necessary to use laser diodes as sources (high speed and lower fibre dispersion) and APD's as detectors. The signal amplification is normally achieved by the use of bipolar transistors (FET's are also used at DS-3 rates) as low noise amplifiers.

Reported receiver sensitivities achieved in laboratory systems are listed below:

45 Mb/sec	-54 dBm (8)
100 Mb/sec	-46 dBm (10)
274 Mb/sec	-44 dBm (9)
400 Mb/sec	-38 dBm (11)
800 Mb/sec	-33 dBm (12)

It is generally assumed however, that systems with capacities of 274 Mb/sec or higher are still in the early development stage, mainly as a result of inadequate laser performance.

Sophisticated laser biasing schemes must be employed in the transmitter portion of the repeater in order to accommodate the aging of the laser.

9.3 LOW CAPACITY DATA LINKS

In order to transmit binary data at low bit rates one requires dc-coupling between the data source and the LED driver as well as between the detector and the dc-coupled amplifier.

The LED (or laser) output power must be somewhat reduced so that the peak drive current does not exceed the average operating current of the source. This normally results in a decrease of output power by about 3 dB.

The signal detection and processing is accomplished in the same way as in the higher capacity systems.

The expected receiver sensitivity for rates up to 65 kb/sec is in the range of -50 to -60 dBm, being limited largely by the dark current of the detector and the 1/f noise of the transistors in the receiver.

A back-to-back configuration of the transmitter and a receiver forms a typical repeater. The repeater may be a fully regenerative kind (with timing extraction) or not depending on whether the transmission rate is fixed or not.

Nippon Electric Co. has a DC to 250 kb/sec. system available with the transmitter - receiver spacing of 30 dB and 40 dB for an LED and a laser source respectively.

When multiplexing of several channels is required either time division multiplexing (TDM) or frequency division multiplexing (FDM) scheme may be used. However, a reduction of cost, size and an increased flexibility can be achieved if FDM is used for multiplexing low capacity channels. This can be accomplished by FSK (frequency shift keying) modulating the data and then frequency multiplexing it. For instance up to 20 channels, 9.6 kb/sec. each may be multiplexed using very simple FSK modulator. The expected repeater spacing for such a system using an LED as a source is approximately 20 dB.

9.4 HYBRID TRANSMISSION OF DATA AND ANALOGUE

The FDM multiplexing scheme described in section (8.3) is perhaps a best approach to a simultaneous transmission of data and analogue via an optical fibre. The analogue signal such as video may be transmitted as a baseband channel and the FSK data channels may be transmitted at carrier frequencies. This really is an analogue system and suffers the same limitations as those described in section (8.1).

Another way of transmitting data and analogue is to use pulse position modulation (PPM) in conjunction with the FDM scheme. This is normally accomplished by converting the electrical analogue signal into optical pulses. Such an approach eliminates the source nonlinearity problem and consequently higher transmitter - receiver spacings may be obtained.

A system operating on this principle is available from Laboratoires de Marcoussis (France). Here a laser source has been used (17 dBm peak power coupled into the fibre) and the PIN detector with the receiver sensitivity of -30 dBm (S/N = 45 dB) for a maximum bandwidth of 4 MHz.

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10. FAULT LOCATION FOR FIBER OPTIC CABLES AND REPEATERS

by T. Witkowicz

The supervision and maintenance of the fibre optic transmission system is required in much the same way as it is in the case of the conventional communication link. The performance of the system has to be monitored during its operation and fault locating must be provided in the event of a system failure.

10.1 REPEATER FAULT LOCATING

As mentioned in section 9.2 the coding of the binary signal into a higher bit rate format can provide an error monitoring scheme without the interruption of transmission. This is accomplished by detection of code violations such as an occurrence of 3 consecutive zeros or ones in a 2-level AMI code (1). In the event the rate of violations increases beyond an acceptable level a fault locating search is required in order to determine the cause of system failure.

Fibre optic transmission systems require a somewhat different procedure for fault location than the conventional systems. In order to locate a faulty line segment either an additional fault locating line has to be installed or a repeater looping capability provided at each repeater. The first approach requires an additional transmitter module to be connected to a spare fibre and all repeaters in each repeater station. The second perhaps a less costly method requires a built-in capability in a repeater to connect its receiver to a transmitter in the opposite direction link.

Once the fault line is successfully located, the relevant tests may be performed. The required tests are: a measurement of transmission properties of the cable, the measurement of transmitted and received light power at each end and the test of electronic circuitry.

10.2 LOCATION OF CABLE FAULTS

Once the repeater electronic and opto-electronic components have been examined, it may be necessary to determine the status of the optical cable. If no fibre breaks have occurred the fibre attenuation and bandwidth may be measured using an oscillator, light source, a detector and a selective voltmeter. The received and transmitted light power can also be determined using part of the above equipment. In the case the above tests prove negative the repeater may have to be replaced.

The opto-electronic components required for these tests (available from BNR and from many other laboratories involved in fibre optics) can easily be put together into a compact test unit, such as the one available from STC (England) (2).

In the event of cable breaks, time domain reflectometry (3.4) may be used to find the faulty points. This method is based on a radar principle, owing to the fact that the light is reflected at a fibre break. The sensitivity and range of this test method are largely dependent on the amount of light power that can be launched into the fibre and on the detector bandwidth. With a fixed light power input the trade-off is between the range and accuracy. Typical figures reported (4) are: a range of 33 dB (one way fibre attenuation) and an accuracy of 2.5 m with a peak light input power of 4 W. Further development of this test is required however, mainly in order to develop a convenient plug-in type os a test unit that can be used in the field. It is believed that once the test units are available the testing procedures will be quite straightforward and that little training of technical personnel will be required. In training of personnel the main stress will have to be put on the handling of the fibre connectors and the fibre itself.

If the cable is pressurized then pressure monitoring may be used to locate damaged cable sections, however, trends would indicate that fibre cables will generally be unpressurized.

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11. EXPERIMENTAL AND FIELD TRIAL SYSTEMS

M. Larose N. Toms K.Y. Chang

This section lists several systems which have been reported as being under trial, and includes information gathered on visits to some sites. Although not exhaustive, these trials are representative of fiber optic transmission systems currently under development.

11.1 THE BELL SYSTEM FIELD TRIAL AT ATLANTA

11.1.1 Summary

The Atlanta field trial demonstrated the feasibility of transmitting DS-3 rate (44.736 Mbit/s) digital telephony over a fiber optic cable in an outside plant environment. The trial was begun in January 1976, using Bell Telephone Laboratories (BTL) components and Western Electric cable.

11.1.2 System Description

Signals at DS-1 (1.544 Mbit/s) rate from a D3 channel bank were multiplexed up to the DS-3 rate. The bipolar signal was converted to a NRZ binary signal, and parity bits inherent in the DS-3 bit stream were used for error detection. A GaAs injection laser was directly modulated, with feedback for stabilisation. The signal was transmitted through a cable, described below, which contained 144 fibers, and was laid in a 658 metre length duct. By looping the signal back and forth through different fibers long system lengths could be achieved. An optical loss of 54 dB was acceptable for 10^{-9} error rates. The maximum length of fiber achieved for repeaterless transmission was 10.95 km, and 7 km was guaranteed in any practical system. Using repeaters total system lengths of up to 64 km were built.

11.1.3 Components

a) <u>Fiber</u>

The fiber was mainly BTL manufactured, 50 um core diameter graded index. One of the two cables in the experiment used 25% Corning fibers. The attenuation of the fibers in the cables varied, with an average value of 6 dB/km at 0.82 um. Out of 138 fibers measured in one cable, only 5 exceeded 10 dB/km.

b) <u>Cable</u>

The fibers were packaged in accurately dimensioned ribbons of 12 fibers each. Twelve of these ribbons were then stacked to give an accurate array of 144 fibers, approximately 6 mm square.

This approach was taken with the idea of facilitating bulk splicing and connecting of 144 fibers to 144 fibers at one time. The fiber array was twisted in a loose helix, wrapped in paper and coated with a polyethylene sheath. This assembly was covered by polyolefin twine applied helically, then by a helical array of metallic strength steel (Bell Labs Dec. '76) members and finally by a polyethylene outer sheath 12 mm in diameter. No fiber breaks were reported with a load of 1800 Newtons, and at 4500 N less than 15% of the fibers were broken.

c) Splices

The mass splicing philosophy (144 fibers to 144 fibers) gave a 0.8 dB mean loss. (Laboratory trials had given mean losses of 0.3 dB.) For the system lengths reported above, however, single fiber to single fiber splices were used, with losses of below 0.1 dB.

Some caution is needed in comparing losses in different splices and connectors, since losses are very dependent on the mode configuration at the joint, due to launching conditions, fiber NA, distance from source, etc.

d) Connectors

No losses have been published for the bulk connectors. Jack-plug type single fiber connectors were used for connecting up the patchboard in the experiment. For this, fiber was placed in micro-coax packaging and standard BNC shells used for connectors. The tip of the connector was a transparent silicon rubber cushion to protect the fiber from mechanical shock and to provide index matching. Mean losses for such jack plug connections were reported as being 1 dB. Several hundred connect/disconnect cycles have been reported.

e) Opto-Electronic Components

The GaAs injection laser launched 1 mW peak power pulses into the fiber. Life times of 100,000 hours MTBF at room temperature have been extrapolated for these devices. The extinction ratio of the laser was reported to be 15:1. The avalanche photodiode (APD) used as a detector used a voltage between 300 and 400 V. The excess noise factor was 5 or 6, and the APD was run at a gain of 80.

The circuitry had a 70 MHz bandwidth to avoid equalization in the pre-amplifier, at a slight cost in SNR.

f) General

The duct through which the cable was pulled had one 180° bend and two 90° bends. Standard cable pulling equipment was used. BTL spokesmen see no problem in pulling 1 km of cable, and 2 km is regarded as possible. Experiments at DS-1 rates over this link are planned using LED's and PIN photodiodes but no details have been published.

11.1.4 Comments

The field trial is the result of a concerted BTL effort on all aspects of fiber optics, and clearly shows the technical feasibility of fiber optics for use in practical digital links at bit rates up to 44 Mbit/s. Connectors and splices are seen as major areas for improvement, especially in reducing the skill level of personnel needed to implement them.

11.2 REDIFFUSION FIELD TRIAL AT HASTINGS, U.K.

11.2.1 Summary

The Hastings field trial is a demonstration of transmission of a HV TV analogue signal in the trunk environment normally used by Rediffusion. It was installed in March 1976.

11.2.2 System Description

The trial system transmits a video signal on an 8.9 MHz carrier with VSB modulation, transmitting the full lower sideband. The sound is carried by a separate cable (not fiber optics in this trial). The video signal modulates a light emitting diode, which launches 0.125 mW into the fibre. 1427 meters of cable (with two fibers, each carrying a separate signal) introduces 19 dB of loss between the LED and a PIN photodiode detector.

11.2.3 Components

a) Fiber

The fiber was Corning silica step index type, of NA 0.16 and 85 um core diameter.

b) Cable

The cable, manufactured by BICC, housed two fibers lying loose inside a cavity surrounded by an oval shaped polyethylene sheath, of outside dimensions 7 mm x 4 mm. Two 1 mm diameter steel strength members are included in the sheath.

c) Splices

A copper block is used in which a fine groove has previously been impressed by a length of optical fiber, and in which the ends of the fibers to be joined are carefully butted together and clamped. Index matching fluid is used, and a typical splice loss of 0.3 dB is reported.

d) Opto-Electronic Components

The LED is a Plessey HR954 Burrus-type diode, which has a radiance of 35 watts/sr/cm at 900 nm wavelength, 300 mA drive current.

Lifetimes of 10^7 hours have been predicted for such devices on the basis of extrapolations from high temperature tests.

e) General

The duct through which the cable was pulled included several 90° bends, and already contained a dozen other cables in places. Ducts are 3 in. or 3 1/2 in. diameter salt glaze ducts, and were reported to be extensively silted and rather wet. Lengths of up to 500 m were pulled in at a time, with pulling strains of less than 60 kg.

11.2.4 Comments

The field trial is an example of a possible use of fiber optics for trunking of space division multiplexed analogue video - a system already common in the U.K. using copper pairs, but not common practice in North America. The trial demonstrated the feasibility of such an application, but more development needs to be done on splicing, and the capabilities of cascaded repeater sections, since no results have been obtained on picture quality following a cascade of such repeaters.

11.3 TELEPROMPTER'S CATV ENTRANCE LINK TRIAL AT MANHATTAN

11.3.1 Summary

In this trial CATV signals are carried on optical fibre from a microwave receiver to the headend, both located in the same building. The system was installed in July 1976, using components from Belden Cable Co (Cable), Fiber Communications Inc. (Fiber) and BNR (LED's).

11.3.2 Description

Three television signals were demodulated to baseband at a microwave receiver on the roof of a high rise building in New York city. These signals modulated three LED's, and the resulting analogue optical signals passed through three separate fibers over a distance of 250 metres to Teleprompter's head-end. Detection was effected using PIN photodiodes, and a SNR of 57 dB was reported for the detected signal.

11.3.3 Components

a) Fiber

The fiber, made by Fiber Communications Inc., was of the step index type, with a core diameter of 55 um and outside diameter of approximately 100 um. Fiber loss was 8 dB/km.

b) Cable

The fiber was coated by Belden, and loosely enclosed in a semi-rigid plastic tube approximately 1 mm in diameter. Six such tubes were twisted around a central strength member of KEVLAR, to form a cable 1/4 in. in outside diameter.

c) LED's

The diodes were specially manufactured by BNR, with a smaller emitting area than the usual 75 u. The on axis radiant intensity was between 2 and 3 mW/sr at 150 mA and the bandwidth of the devices was between 32 and 44 MHz to the 3 dB point. Maximum drive current for these devices was 200 mA. The LED's were supplied with a "pigtail" of fiber already attached, which was then spliced to the fiber in the cable.

11.3.4 Comments

Although the cable environment for this trial is sheltered compared with that in most other trials, the 57 dB SNR transmission required is very stringent, and the link demonstrates more than adequate linearity for baseband transmission of TV signals.

11.4 PLESSEY EXPERIMENTAL LINK AT TAPLOW, U.K.

11.4.1 Summary

The Taplow experiment uses 740 meters of cable in a duct as a test bed for analogue video and digital telephony transmission. The cable was installed in December 1974.

11.4.2 System Description

The cable was installed through two parallel PVC ducts, each of 50 mm diameter, running 285 meters from the laboratory, through two 45° bends of radius 2 metres, and one 90° bend. 740 metres of cable was installed, going from the laboratory through one duct, executing a 180° bend in a manhole and returning through the second duct. The attenuations of the two fibers in the cable were measure to be 12.6 and 7.4 dB (17 dB/km and 10 dB/km respectively).

For analogue transmission tests, a baseband video signal, with its sound on a 6 MHz carrier, was multiplexed with a 10.7 MHz FM audio signal. A LED standing current of 100 mA was modulated to a depth of 50% by the video input signal. Detection used a PIN photodiode followed by a FET cascade input stage preamplifier with feedback. AC coupling, down to 1 Hz, is used. CCTV transmission specifications were easily met over the link, using the full 20 dB of attenuation possible, and 2 km links were considered easily achievable.

The digital transmission use 8.448 Mbit/s transmission, encoded as "differential biphase" (i.e. transmitted at twice the signal bit rate).

The LED was driven from "off" to a peak drive current of 200 mA from a 12 V, 30 mA source, This peak drive current corresponded to 50 uW launched into the fiber. Detection used a PIN photodiode with an equaliser between the diode and the amplifier. Error rates of 10^{-9} were achieved for detected peak power levels of 3.7 nW allowing a fiber loss of over 40 dB.

11.4.3 Components

a) Fiber

The fiber was Corning step index silica fiber, of NA 0.18, core diameter 85 um, overall diameter 125 um and a 5 um protective coating of Kynar. Cabling increased the fiber attenuation by between 1 and 2 dB/km to the figures given above.

b) Cable

The BICC-made cable was identical to that used by Rediffusion, and already described. Pulling tensions, using liquid paraffin as lubricant, were kept below 150 N. A normal cable laying team was used.

11.4.4 Comments

This installation was one of the earliest "in-duct" experiments. The analogue experiment has been run for over 18 months without any significant degradations.

11.5 JAPANESE POWER COMPANIES TRIAL IN TOKYO

11.5.1 Summary

There are currently six trials of transmission by fiber optics alongside electrical power cables, of which three are in Tokyo and three in Kansai. In each case three companies or groups, namely NEC-Sumitomo, Hitachi, and Fujitsu - Furukawa have their own trial. Trials in Kansai began in April 1976, while those in Tokyo began in June 1976.

11.5.2 System Description

The Fujitsu - Furukawa trial at Tokyo runs approximately 2.7 km. The first 1 km is in an underground tunnel containing power cables, followed by 700 m of aerial cable and a further 1 km in a conduit. Both ends of the cable are terminated in jack panels. By patching at these panels, repeater spacings of 5.7 km have been achieved. The signal transmitted is a 6.2 Mbit/S digital signal, with orderwire and supervisory signals on a FM carrier above the baseband digital signal. Powering of repeaters is by chargeable batteries with a 10 hour reserve in case of loss of power.

The Fujitsu - Furukawa installation at Kansai is similar, linking two computers with the choice of 6.3 Mbit/S or 240 kbit/s signals.

The NEC-Sumitomo system, while similar in route and traffic to the above, encodes the 6.3 Mbit/S signals and the orderwire and supervisory signals together by differential pulse position modulation, using a bandwidth expansion of about 5, giving an error rate of 10 at a received power level of -63 dBm.

11.5.3 Components

a) Fiber

Step-index silica fiber and Selfoc fibers are used by NEC-Sumitomo, with losses of 4.6 dB/km and 7.3 dB/km respectively. Hitachi - Hitachi Wire and Cables use W-type silica fibers, believed to be of their own manufacture. Fujitsu - Furukawa use step-index Corning fiber with 7.7 dB/km attenuation after cabling.

b) Cable

All cables have four fibers in them, and are made by the organisations responsible for the trial. They are of the kind illustrated in section 5, figures 5.6, 5.7 and 5.8.

c) Light sources

Fujitsu - Furukawa used GaAlAs injection lasers, launching a mean power of -6 dBm into the fiber. The other companies are also believed to have used lasers.

d) Detectors

Fujitsu - Furukawa used Si APDs followed by a high impedance front-end amplifier. Error rates of 10 with an optical power level of -57 dBm were reported.

e) Splices

NEC-Sumitomo used V-groove splices, with an average loss of 0.4 dB for a 40 um core diameter step-index fiber. Total loss for 8 splices and 4 connectors was 17.8 dB in one fiber, 20.6 dB in the other.

Fujitsu - Furukawa reported a mean splicing loss of 0.3 dB.

11.5.4 Comments

These trials demonstrate the use of fiber in an environment with a severe electromagnetic radiation interference problem.

11.6 NASA COMMUNICATION EXPERIMENTS AT CAPE KENNEDY

11.6.1 Summary

Unlike the previous trials, this trial is more a series of laboratory experiments. It is included here because of the wide range of signals being transmitted, and the fact that the environment is unique.

11.6.2 System Description

NASA has 13,000 miles of 5 MHz bandwidth cable installed at Cape Kennedy to carry a wide range of signals (telemetry of rocket instruments during take-off, television monitors, audio communications, etc.). They have carried out a series of experiments using fibre optics to carry these signals. In their first experiment a 1 kft 19 fiber bundle (from Corning) was used at the link. Over this link NASA transmitted simultaneously: three DSB AM audio channels (each carrying 112 VF channels), at 7, 10 and 13 MHz, and three video channels on NTSC channels 2, 3 and 4 (54 to 72 MHz). A second experiment using the same cable transmitted simultaneously: three FM channels of 1 MHz each (carrying 112 VF channels each) at 14, 18 and 22 MHz; three 1 Mbit/s digital PSK channels at 30, 38 and 50 MHz, and three video channels, at 90 MHz, 70 MHz and baseband. A scheme proposed for installation at the end of 1975 used single fibers per channel in 6 kft lengths of 10 fibre cable. This installation was to be less ambitious in its multiplexing target - each fiber carrying only 10 MHz of information, either in the form of 10 MHz PSK data channels, or TV, or FM analogue channels carrying voice or telemetry measurements.

No figures accurately reflecting the system linearity have been published, although 55 dB SNR was reported for the video in the first scheme reported above, and a SNR of 64 dB in the 13 MHz audio band. Experimental results preferred the use of FM for video transmission.

11.6.3 Components

NASA experimented with HeNe lasers and external modulators, although all the above experiments used LED's. Both acousto-optic and electro-optic modulators were reportedly sufficiently linear for the 100 MHz system, but no precise figures are available, and the LED was finally selected due to its advantages in size. A TI LED was used for the bundle experiment, and a BNR diode has been chosen for the 6000 ft installation.

11.6.4 Comments

This is one of the few trials looking at frequency division multiplexing of so many channels, and further results should be interesting. It is also worth noting that some specialized, but significantly large, systems are prepared to consider bulky external modulators if these give superior performance.

11.7 DEPARTMENT OF NATIONAL DEFENSE, OTTAWA

11.7.1 Summary

This link, installed in early 1976, transmits video, data and digital telephony over one fiber for a distance of 370 feet using BNR components and Corning fibre.

11.7.2 System Description

Digital telephony was supplied from a D3 channel bank, and the resulting 1.544 Mbit/s signal used to modulate a 12MHz carrier (AM). Data at 100k Baud modulated a 7 MHz carrier (FSK). Video was transmitted at baseband, and the three signals mixed and input to an LED.

The fiber optic cable connected two terminals separated by six floors in the Department of National Defense headquarters in Ottawa. The cable was installed in a transparent acrylic conduit suspended from the ceiling and in 4" steel pipe risers between floors. During installation pulling tensions were kept to less than 20 kg.

An important feature of the link was the fact that signals were introduced into an RF screened room. Also, to guarantee security, signal level at the receive end was continually monitored. A drop in received signal level would interrupt transmission and activate an alarm.

11.7.3 Components

a) <u>Fiber and Cable</u>

The fiber was Corning step index fiber, core diameter 75 u, cladding diameter 125 u, with a KYNAR coating to 132 u total diameter. The fiber attenuation was 20 dB/km with a nominal bandwidth of 20 MHz-km. Six fibers were packaged in the standard Corguide configuration (formerly type "1100", now renamed "1300").

b) <u>LED's</u>

The LED was a BNR 40-3-30. These diodes have a typical radiance of 66W/sr/cm at 840 nm with a typical spectral width at half intensity of 40 nm. The bandwidth (to optical power 3 dB point) is typically 44 MHz with a guaranteed minimum of 32 MHz.

c) Photodetector

The photodetector was a BNR D-5 PIN photodiode.

d) Connectors

The connectors at each end of the link were BNR C-10 connectors. Since the diameter of the Corning fiber was only 132 u, it was necessary to coat the fiber at its end in order to build its outside diameter up to the 1mm needed to fit these connectors.

Since the link was an operational one, in situ attenuation measurements on the connector attenuation were not possible. However, measurements on similar connectors with the same index matching fluid (DC 710) indicated a loss of about 1 dB.

11.7.4 Comments

Provision of the same services with immunity from tapping, and entry into an RF shielded room by conventional techniques would have been very costly. This installation is a good example of the application of the tight guiding (immunity to tapping) and non-inductance (immunity to pick-up) properties of fiber.

11.8 FUTURE TRIALS

Among the systems known to be planned for trial in 1977 or beyond are the following:

1) The British Post Office will experiment with field installations at 8 Mbit/s and 140 Mbit/s. The 8 Mbit/s system will run 12 km between the BPO research laboratories at Martlesham Heath and Ipswich, passing through a switching centre at Kesgrave, 5 km from Martlesham. Lasers will be used as light sources, using a plane glass reflector to deflect some light on to a photodetector in order to monitor the DC bias. Avalanche photodiodes will be used. Line transmission will use a 5B6B code, offering some error monitoring capability. Although non return to zero signals will be used initially, return to zero will be used later, with the DC bias on the laser well below threshold to extend laser life. BICC cable with 5 dB/km Corning fiber is to be used.

   The 140 Mbit/s transmission experiment will operate over the Martlesham to Kesgrave section of the above route (5 km). Components will be the same as used for the 8 Mbit/s system, except that the laser bias control circuitry will be more elaborate, and coding will be 7B8B. BPO express interest in using simpler codes in future if fiber bandwidths permit.

   Both trials are scheduled for 1977.

2) Plessey (U.K.) will install a 12 km fiber optics trial along Post Office ducts running between Maidenhead and Slough. The trial will include two repeaters in manholes at 3 km from each end of the link. A Plessey LED will be used with a target of 200 mW launched iunto the fiber at 200 mA drive current. The detector will be an APD followed by a bipolar transimpedance amplifier. A constraint on the repeater design is the small amount of power available due to BPO regulations - 50 mA at 50 V. Unlike the BPO trial, coding will be 3B4B. BICC cabled Corning fiber will be used. The trial is scheduled for late 1977.

3) The Deutsche Bundespost (German Post Office) plans to link two switching centres 4.3 km apart in West Berlin with optical fiber. The system will operate at 34 Mbit/s, with a target error rate of 10 per km of link over a period of 50,000 hours. The system is not expected to be installed before 1979.

4) The Japanese Ministry of International Trade of Industry (MITI) is planning the creation of a "wired city" in the town of Higashi-Ikoma with a wide range of broadband communications services provided. Initially the system was to use coaxial cable, but fiber has been chosen as more economical. The system will serve about 300 homes, each home having an interactive terminal of a key board, a TV set and control electronics. The system will include three fiber optic trunk cables of 36 fibers each, connecting the head-end facility to a subcenter. The video switches at the subcenters serve up to 14 distribution cables, each containing 24 optical fibers, (two to each of 12 subscribers). Companies involved are Fujitsu Ltd. (control center and digital data interfaces), Sumitomo Electric Industries Ltd. (optical fiber transmission system), Matsushita Electric Industries Co. (studio equipment and subscriber terminals) and Arthur D. Little (consultants). Light sources will be from BNR. This is an extremely large project, reported to be budgeted at $17M, and scheduled to be spread over several years.

5) The Japanese Post Office (NTT) is planning a field trial of 32 Mbit/s inter-office transmission. NTT has expressed confidence that, in the congested environment of Japan, fiber optics will be used to accommodate much of the inter-office telephony growth predicted.

6) CSELT in Italy have already laid a 984 metre long fiber cable in a duct at Turin. Experiments on transmission at 8 Mbit/s and 34 Mbit/s are planned.

7) GTE have announced plans for a field trial in the Los Angeles area. T1 bit rate (1.544 Mbit/s) signals will be transmitted 10 km between two switching centres, with repeaters. In an initial phase, 4 repeaters will be used on one fiber, 3 on another. In a later phase it is hoped to reduce the number of repeaters to 2 and 1 respectively. The cable will be a heavily reinforced General Cable product with 6 fibers, although the same cable could accommodate 30 fibers.

Fiber is from Corning with a cabled attenuation of less than 6 dB/km. The cable and repeater housings will be pressurized. Transmission will be uncoded with a unipolar signal, and one of the 24 channels in the T1 format will not be available for voice, but will rather be used for error monitoring. Splices will use a V-grove with attenuations of 0.5 dB predicted. The first phase is scheduled for April 1977.

8) STL (UK) will carry out a field demonstration of a 140 Mbit/s system. The system will operate in Post Office ducts between Hitchin and Stevenage - a distance of 9 km, with regenerative repeaters spaced at 3 km. Repeaters will be housed in standard Post Office repeater cases. The cable will contain three graded index fibers with a 5 dB/km attenuation. Cable structure will consist of a polythene sheath and a central strength member, with four metallic conductors for power feed. The system is scheduled for the second half of 1977.

9) GEC (UK) have developed a fiber optic cable with under 5 dB/km attenuation, and are carrying out trials on a 625 metre length in a Post Office duct along the A13 road. A 30 channel PCM system (presumably at 2 Mbit/s) is used in the trial, which is primarily intended to test the fiber.

10) A.T. & T. plans to conduct an experiment in Chicago. Franklin central office will be connected to Wabash central office (1.4 km) and to Brunswick building (0.8 km). Voice, data and video, including "live" traffic, will be transmitted at 44.7 Mbit/s. The fiber will be of Western Electric manufacture with an attenuation of 6 dB/km, and will be cabled in two strips of twelve fibers each. (These strips will be of the same form as those in the 144 fiber cable used at Atlanta). Both lasers and LEDs will be used in the experiment, with avalanche photodiodes as detectors. No repeaters will be needed between offices. The experiment is scheduled for mid 1977.

11) Bell Northern Research/Bell Canada plan a joint exploratory trial. The trial is to run between Belmont and Ontario St. central offices in Montreal (1.5 km), and will carry 6.3 Mbit/s digital telephony initially. The light source will be the BNR 40-2-30-3 LED, and the detector will be a BNR D-5-2 photodiode. The LEDs will launch 220 uW into the BNR 7-2-B optical fiber at 250 mA drive current. Six of these fibers will be cabled by Northern Telecom. The signal will be converted to binary and encoded, using a 2B3B code. Splicing will be performed in manholes. The trial is scheduled for late 1977.

The salient features of these trial systems are summarized in figure 1.11.1.

FOOTNOTE:

In view of the somewhat confusing array of bit rates quoted above, the following guide is offered to the reader. North American digital telephony follows a hierarchy of bit rates, of which the first three members are:

DS-1 (1.544 Mbit/s), DS-2 (6.312 Mbit/s) and DS-3 (44.736 Mbit/s).

In the text these figures are frequently rounded to 1.5, 6.3 and 44.7 respectively. These rates are often referred to as T1, T2 and T3, respectively, although strictly this terminology is incorrect. The first two members of the Japanese hierarchy also operate at DS-1 and DS-2 rates, but the third is 32 Mbit/s (round figures). The European standards are, in round figures, 2 Mbit/s, 8 Mbit/s and 34 Mbit/s.

TABLE 11.1a

	BTL/WE	REDIFFUSION	TELEPROMPTER	PLESSEY	JAPANESE POWER COS.	DND	BPO (a)
Route length (km)	0.65	0.74	0.24	0.74	3 (max)	0.12	12
# of fibers in cable	144	2	6	2	4	6	2
Cable Manufacturer	WE	BICC	Belden	BICC	See text	Corning	BICC
Fiber loss (dB /km)	6 (mean)	13	8	17 & 10	from 4.6	20	5
Fiber Manufacturer	WE/Corning	Corning	Fiber Communications	Corning	See text	Corning	Corning
Analog (A) or Digital (D)	D	A	A	A/D	D/A	A/D	D
Signal type	44.7 Mbit/S	CATV at 8.9 MHz	Baseband TV	Baseband TV + Sound 8 Mbit/S	6.3 Mbit/S + voice	1.5 Mbit/S; Baseband video;data	8 Mbit/S
Repeater Spacing (km)	10.9 (max)	1.4	0.24	1.48		0.12	?
Light source	Laser (BTL)	LED (Plessey)	LED (BNR)	LED (Plessey)	Laser	LED (BNR)	Laser
Detector	APD	PIN	PIN	PIN	APD	PIN	APD
Date started or due to start	Jan/76	March/76	July/76	Jan/75	April/76	June/76	1977
Location	Atlanta	Hastings (UK)	New York	Taplow (UK)	Tokyo and Kansai	Ottawa	Martlesham (UK)
Remarks	1st major telephony trial	1st trial in commercial CATV network	head-end entrance link	1st trial of fiber in field	large scale trial in demanding electromagnetic environment	secure link	Significant step towards inter-office use in UK

TABLE 11.1b

	BPO (b)	PLESSEY	GERMAN P O	JAPANESE MITI	NTT (JAPAN)	CSELT (ITALY)	GTE (US)
Route length (km)	5	12	4.3	Area of 1 km^2 covered	60 (?)	.984,2*,4**	10
# of fibers in cable	2	2	?	36 & 24	8 (?)	6	6
Cable Manufacturer	BICC	BICC	?	Sumitomo	?	Pirelli	General Cable
Fiber loss (dB / km)	5	5	?	?	?	4.5(best)	6
Fiber Manufacturer	Corning	Corning	?	?	?	Corning	Corning
Analog (A) or Digital (D)	D	D	D	A/D	D	D*	D
Signal type	140 Mbit/S	8 Mbit/S	34 Mbit/S	TV & Data	32 Mbit/S	34 Mbit/S*	1.544 Mbit/S
Repeater Spacing (km)	?	6 (max)	4.3 (?)	?	?	–	3.3 (max)
Light source	Laser	LED	?	?	?	LED*	?
Detector	APD	APD	?	?	?	PIN* +APD**	?
Date started or due to start	1977	Late '77	1979	Nov/76 1st phase	mid 1977(?)	March/76	April/77
Location	Martlesham (UK)	Maidenhead (UK)	Berlin	Higashi Ikoma, Japan	Tokyo(?)	Turin	Los Angeles
Remarks			Many components still up for tender	Largest scale field trial of all, creating a wired city with fibers		Figures & components with *'s were obtained in the lab, not on the installed cable	Features field repeaters

TABLE 11.1c

	STL (UK)	GEC (UK)	A T & T	BNR/BELL CANADA
Route length (km)	9	.625	2.2	1.5
# of fibers in cable	3	?	24	6
Cable Manufacturer	STL	GEC	WE	Northern Telecom
Fiber loss (dB / km)	5	5	6	13
Fiber Manufacturer	STL	?	WE	BNR
Analog (A) or Digital (D)	D	D	D	D
Signal type	140 Mbit/S	2 Mbit/S	44.7 Mbit/s	6.3 Mbit/s
Repeater Spacing (km)	3	.625	1.4 (max)	1.5
Light source	Laser (?)	?	Laser & LED	LED
Detector	APD (?)	?	APD	PIN
Date started or due to start	Late/1977	Late/1976	mid 1977	late/1977
Location	Hitchin (U.K.)	U. K.	Chicago	Montreal
Remarks		Principally a cable test	Will carry live traffic	Will test fiber in severe climate. Splices will be made in ducts.