HEWLETT PACKARD

APPLICATION NOTE 1000

Digital Data Transmission With the HP Fiber Optic System

Fiber optics can provide solutions to many data transmission system design problems. The purpose of this application note is to aid designers in obtaining optimal benefits from this relatively new technology. Following a brief review of the merits, as well as the limitations, of fiber optics relative to other media, there is a description of the optical, mechanical, and electrical fundamentals of fiber optic data transmission system design. How these fundamentals apply is seen in the detailed description of the Hewlett-Packard system. The remainder of the note deals with techniques recommended for operation and maintenance of the Hewlett-Packard system, with particular attention given to deriving maximum benefit from the unique features it provides.

ELECTRICAL WIRE VS. FIBER OPTICS

In fiber optic cables, the signals are transmitted in the form of energy packets (photons) which have no electrical charge. Consequently, it is physically impossible for high electric fields (lightning, high-voltage, etc.) or large magnetic fields (heavy electrical machinery, transformers, cyclotrons, etc.) to affect the transmission. Although there can be a slight leakage of flux from an optical fiber, shielding is easily done with an opaque jacket, so signal-bearing fibers cannot interfere with each other or with the most sensitive electric circuits, and the optically-transmitted information is, therefore, secure from external detection. In some applications, optical fibers carry signals large enough to be energetically useful (e.g., for photocoagulation) and potentially harmful, but in most data communication applications, economy dictates the use of flux levels of 100μW or less. Such levels are radiologically safe and in the event of a broken or damaged cable, the escaping flux is harmless in explosive environments where a spark from a broken wire could be disastrous. Jacketed fiber optic cables can tolerate more mechanical abuse (crush, impact, flexure) than electrical cables of comparable size; moreover, fiber optic cables have an enormous weight and size advantage — for equivalent information capacity. Properly cabled optical fibers can tolerate any kind of weather and can, without ill-effect, be immersed in most fluids, including polluted air and water.

Bandwidth considerations clearly give the advantage to fiber optics. In either parallel- or coaxial-wire cable, the bandwidth varies inversely as the square of the length, while in fiber optic cable it varies inversely as only the FIRST power of the length. Here are some typical values for length, ℓ, in metres:

(1) $f_{3dB} = \frac{12{,}000}{\ell}$ MHz for HFBR-3001 to 3005 cables

(2) $f_{3dB} = \frac{225{,}000}{\ell^2}$ MHz for typical 50Ω coax (RG-59)

For example, if ℓ = 100m, the 3dB frequency is only 22.5MHz for the coax cable, but for the fiber optic cable it is 120MHz.

The limitations of fiber optics arise mainly from the means for producing the optical flux and from flux losses. While the power into a wire cable can easily and inexpensively be made several watts, the flux into a fiber optic cable is typically much less than a milliwatt. Wire cable may have several signal "taps"; multiple taps on fiber optic cables are economically impractical at present.

The losses in a point-to-point fiber optic system are insertion loss at the input and output, connector loss, and transmission loss proportional to cable length. Variations in these losses require a receiver with a dynamic range capable of accommodating these variations and yet able to provide adequate BW (bandwidth) and SNR (signal-to noise) ratio at the lowest flux level. Fortunately, no noise is picked up by a fiber optic cable so the receiver SNR at any BW is limited only by the noise produced within the receiver.

Fiber optics is not the best solution to every data transmission problem; but where safety, security, durability, electrical isolation, noise immunity, size, weight, and bandwidth are paramount, it has a clear advantage over wire.

FIBER OPTIC FUNDAMENTALS

Flux coupled into an optical fiber is largely prevented from escaping through the wall by being re-directed toward the center of the fiber. The basis for such re-direction is the index of refraction, n_1, of the core relative to the index of refraction, n_2, of the cladding.

Index of refraction is defined as the ratio of the velocity of light in a given medium to the velocity of light in a vacuum.

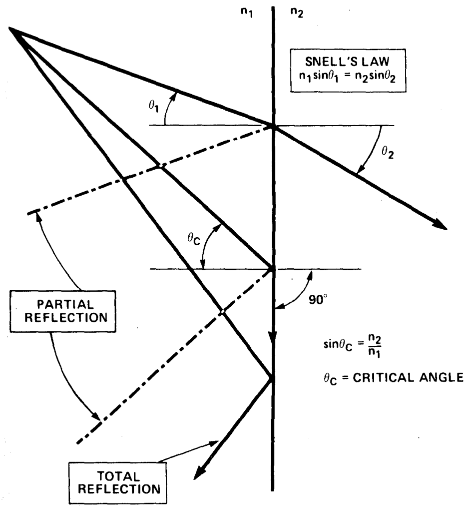


Figure 1. Snell's Law.

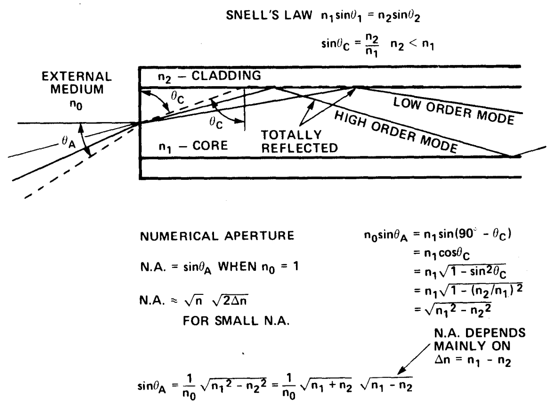


Figure 2. Total Internal Reflection.

As a ray of light passes from one medium into another of a different index of refraction, the direction changes according to Snell's Law:

(3) $n_1 \sin\theta_1 = n_2 \sin\theta_2$ SNELL'S LAW

This is illustrated in Figure 1. Notice that the relationship between the angles is the same, whether the ray is incident from the high-index side (n_1) or low-index side (n_2). For rays incident from the high-index side, there is a particular incidence angle for which the exit angle is ninety degrees. This is called the critical angle. At incidence angles less than the critical angle, there is only a partial reflection, but for angles greater than the critical angle, the ray is totally reflected. This phenomenon is called TOTAL INTERNAL REFLECTION (TIR).

Numerical Aperture.

Rays within the core of an optical fiber may be incident at various angles, but TIR applies only to those rays which are incident at angles greater than the critical angle. TIR prevents these rays from leaving the core until they reach the far end of the fiber. Figure 2 shows how the reflection angle at the core/cladding interface is related to the angle at which a ray enters the face of the fiber. The acceptance angle, θ_A, is the maximum angle, with respect to the fiber axis, at which an entering ray will experience TIR. With respect to the index of refraction, n_0, of the external medium, the acceptance angle is related to the indices of refraction of the core and cladding. When the external medium is air ($n_0 \approx 1$), the sine of the acceptance angle is called the NUMERICAL APERTURE (N.A.) of the fiber:

(4) NUMERICAL APERTURE, N.A. = $\sin\theta_A$

The derivation in Figure 2 applies only to meridional rays, i.e., rays passing through the axis of the fiber; skew rays (non-meridional) can also be transmitted, and these account for the observation that the reception and radiation patterns of optical fibers are not perfect step functions at the acceptance angle. For this reason, the practical definition of N.A. is somewhat arbitrary.

Modes of Propagation

Within the limits imposed by the N.A., rays may propagate at various angles. Those propagating at small angles with respect to the fiber axis are called LOW-ORDER MODES, and those propagating at larger angles are called HIGH-ORDER MODES. These modes do not exist as a continuum. At any given wavelength, there are a number of discrete angles where propagation occurs. SINGLE-MODE fibers result when the core area and the N.A. are so small that only one mode can propagate.

In addition to high- and low-order modes, there are others, called LEAKY MODES, which are trapped as skew rays — partly in the core, but mostly in the cladding where they are called CLADDING MODES. As implied by the term, leaky modes do not propagate as well as the more nearly meridional modes; their persistence, depending mainly on the structure of the optical fiber, ranges from less than a metre to more than fifty metres. The presence of leaky modes will, of course, affect the results obtained in measurement of N.A. and transmission loss, making them both artificially high. For this reason, N.A. is usually specified in terms of the EXIT N.A. for a fiber of length adequate to assure that leaky modes have effectively disappeared.

Since most leaky mode propagation is in the cladding, it can be "stripped." Such cladding mode stripping is done by surrounding the unjacketed fiber with a material having a refractive index higher than that of the cladding. EXIT N.A. is defined as the sine of the angle at which the radiation pattern (relative intensity vs. off-axis angle) has a particular value. This value is usually taken at 10% of the axial (maximum) value.

Transmission Loss

Regular core (non-leaky) modes also exhibit transmission losses. These are due to (1) scattering by foreign matter, (2) molecular (material) absorption, (3) irregularities at the core/cladding interface, and (4) microbending of the optical fiber by the cable structure. The first two loss mechanisms depend on the length of path taken by a ray; the third depends on the number of reflections of the ray before it emerges. It is clear from Figure 2 that the higher order modes have longer paths and more reflections with consequently higher loss. Larger N.A. fibers permit higher-order-mode propagation and, therefore, exhibit generally a higher transmission loss. Transmission loss is exponential and is, therefore, usually expressed in "dB per km." Coupling loss consideration usually favors larger N.A.

The three main loss mechanisms for coupling between fibers or between fibers and the optical ports of other devices are: (1) relative N.A.'s, (2) relative area of the optical ports, and (3) Fresnel (reflection) loss. In addition to these, there may be coupling loss due to misalignment and/or separation of optical ports. Relative N.A. loss can be ignored (≈ zero dB) whenever the N.A. of the receiving port (fiber or detector) is larger than the N.A. of the source port (flux generator or fiber), otherwise:

$$\text{(5) N.A. LOSS (dB)} = 20 \log \frac{\text{N.A. of Source Port}}{\text{N.A. of Receiver Port}}$$

Relative area loss can be ignored whenever the area of the receiver port is larger than the area of the source port, otherwise:

$$\text{(6) AREA LOSS (dB)} = 20 \log \frac{\text{Diameter of Source}}{\text{Diameter of Receiver}}$$

In applying equation (6) to coupling between single fibers, the diameter to be used is the CORE DIAMETER. If the receiver port is a FIBER OPTIC BUNDLE, the "packing fraction" loss must be added to the area loss, even when the area of the bundle is larger than the area of the source port.

$$\text{(7) PACKING FRACTION LOSS (dB)} = 10 \log \frac{\text{Active Area}}{\text{Total Area}}$$

"Active area" is the sum of areas of the cores of individual fibers, and "total" area is that of the bundle.

Fresnel loss occurs when a ray passes from one medium to another having a different index of refraction. Part of the flux is reflected; the fraction transmitted is described by the transmittance, τ, so the loss is:

$$\text{(8) FRESNEL LOSS (dB)} = 10 \log \frac{1}{\tau} = 10 \log \frac{2 + \frac{n_x}{n_y} + \frac{n_y}{n_x}}{4}$$

n_x = index of refraction of medium x
n_y = index of refraction of medium y

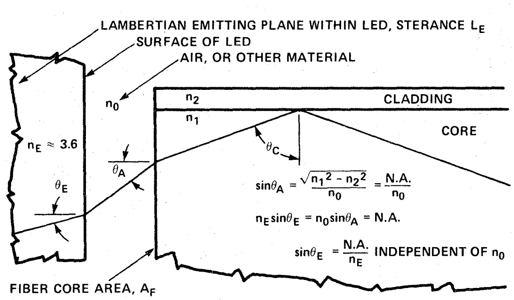
It is clear from equation (8) that the loss is the same in either direction. If two fibers are joined with an air gap between their faces, taking $n_x = 1$ for air and $n_y = 1.49$ for the cores of the fibers, the fiber-to-air Fresnel loss is 0.17dB. The air-to-fiber loss is the same, so the total airgap loss is 0.34dB. If several such connections are made, the loss could be high enough to make it worthwhile to use a coupling medium, such as silicone, to remove the air gap. Often, however, connector loss comes mainly from a gap deliberately inserted to prevent scratch damage to the fiber face and to reduce the variability of misalignment loss; i.e., it is sometimes more important to make the connector loss be consistent rather than low.

The use of a coupling medium is more significant when a fiber is coupled to an LED or IRED source. These sources are usually of gallium arsenide, or related substances, with a refractive index of 3.6. With such a high index of refraction, the use of an epoxy cement can reduce coupling loss by approximately 1dB. Figure 3 shows how the flux coupling is derived. If the size of the LED is much less than that of the fiber, a more effective technique is the use of a tiny lens over the LED. If the size of the fiber is smaller, the lens should be on the fiber, rather than the LED.

Rise Time Dispersion

Bandwidth limitation in fiber optics is the result of a phenomenon called DISPERSION, which is a composite of MATERIAL dispersion and MODAL dispersion. Both of these relate to the velocity of flux transmission in the core. Velocity varies inversely as the index of refraction, and if the index of refraction varies over the wavelength spectrum of the source, the flux having a wavelength at which the refractive index is lower will travel faster than the flux having a wavelength at which the index is higher. Thus, all portions of the spectrum of flux launched simultaneously will not arrive simultaneously, but will suffer time dispersion due to differences in travel time. This is MATERIAL DISPERSION. It is reduced by using sources of narrow spectrum (e.g., lasers) or fibers with a core index of refraction which is constant over the source spectrum.

In Figure 2, notice that rays moving parallel to the axis travel a path length which is shorter than that of rays which are not paraxial. Those rays propagating in the higher-order modes will, therefore, have a longer travel time than those in lower-order modes, and simultaneously launched rays will suffer dispersion of their arrival times. This is MODAL DISPERSION. It can be reduced only by reducing the N.A. (smaller acceptance angle) to allow only lower-order modes to propagate.



FLUX COUPLED, $\phi = \pi\tau L_E A_F \sin^2\theta_E$

LED–TO–CORE TRANSMITTANCE $\tau = \left(\frac{4}{2 + \frac{n_E}{n_0} + \frac{n_0}{n_E}}\right)\left(\frac{4}{2 + \frac{n_0}{n_1} + \frac{n_1}{n_0}}\right) = 1 - \left(\text{FRESNEL LOSS}\right)$

WITH AIR, $n_0 = 1.0$, $\tau_1 = 0.65$

$10 \log \frac{\tau_2}{\tau_1} = 1.03$ dB

WITH EPOXY, $n_0 = 1.5$, $\tau_2 = 0.83$

EPOXY DOES NOT AFFECT ACCEPTANCE ANGLE BUT DOES REDUCE FRESNEL LOSS

Figure 3. Acceptance Angle and Fresnel Loss Effects.

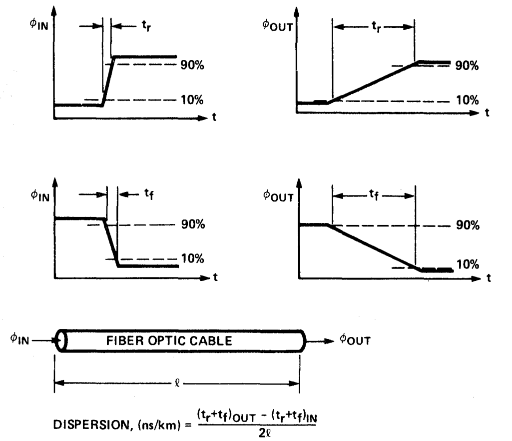


Figure 4. Rise Time Dispersion.

Whether the dispersion is material or modal (or both), it is measured, as shown in Figure 4, by applying positive and negative steps of flux and measuring the rise and fall times at the input and output of a fiber long enough to exhibit significant dispersion. Time dispersion is then defined as

(9) RISE TIME DISPERSION

$$\frac{\Delta t}{\ell}\ (\text{ns/km}) = \frac{1}{2\ell}\left[(t_r + t_f)_{OUT} - (t_r + t_f)_{IN}\right]$$

where ℓ is the length (in kilometres) of the fiber and t_r, t_f are the 10% to 90% rise and fall times.

Flux steps, rather than pulses, are used to avoid incorrect results that source or detector rise and fall times might introduce. Both polarities of step are recommended in order to compensate for non-linearity in either the source or the detector used.

Modulation frequency response of a fiber has a 6dB per octave roll-off, so the effect of rise time dispersion can also be described in terms of a length-bandwidth product:

(10) 3dB BANDWIDTH CONSTANT $= \Delta f \cdot \ell = 0.35 \frac{\ell}{\Delta t}$

Construction of Fiber Optics

Fibers having a sharp boundary between core and cladding, as in Figure 2, are called STEP INDEX fibers. The reflection at the boundary is not a "zero-distance" phenomenon — the ray, in being reflected, is actually entering a minute distance into the cladding and there is some loss. This loss can be seen as a faint glow along the length of unjacketed lossy fibers carrying visible flux. To reduce such reflection loss, it is possible to make the rays turn less sharply by reducing the index of refraction gradually, rather than sharply, from core to cladding. A fiber of such a form is called a GRADED INDEX fiber and the rays propagate as shown in Figure 5. Graded index fiber has not only a very low transmission loss, but modal dispersion is also very low. Higher-order modes do travel longer paths, but in the off-axis, lower-index regions they travel faster so the travel time differential between high-order and low-order modes is not as large as it is in step index fibers.

Graded index fiber has higher coupling loss and may be more costly than step index fiber. It is, therefore, used mainly in applications requiring transmission over many kilometres at modulation bandwidths over 50MHz. For shorter distances and/or lower bandwidths, a variety of step index fibers are available at a variety of costs.

Figure 6 shows the construction of a Hewlett-Packard fiber optic cable. Over the fused-silica, step-index, glass-clad fiber there is a silicone coating to protect the thin

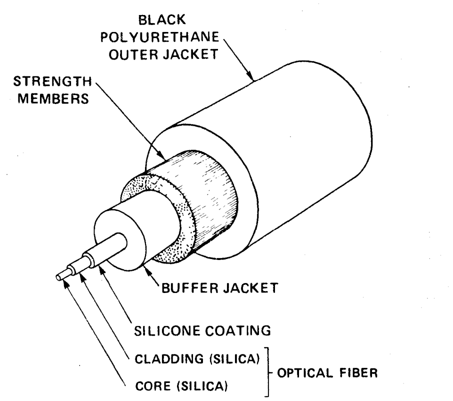


Figure 6. Step Index Fiber Optic Cable Construction.

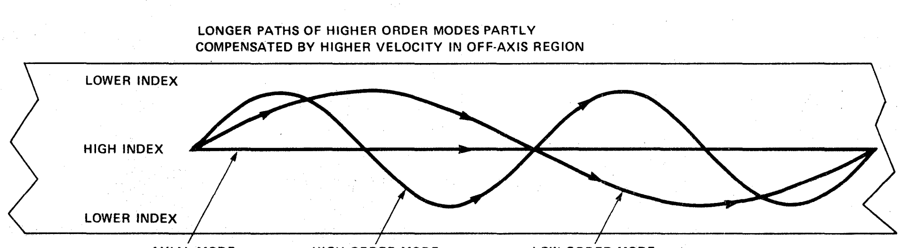


Figure 5. Graded Index Fiber Modes.

APPLICATION NOTES

(20μm) cladding from scuffing. Over the buffer jacket are the tensile strength members, which allow the cable to be pulled through long conduits, and an outer jacket to protect the cable against crush and impact damage. This cable tolerates far more abuse than most wire cable. A sample was laid across the main entrance to the Hewlett-Packard headquarters and factory at 1501 Page Mill Road, Palo Alto. After several weeks of being driven over, night and day, there was no impairment of performance.

Other materials used in step index fibers are glass-clad glass, plastic-clad glass or fused silica, and plastic-clad plastic. These have N.A.'s ranging from less than 0.2 to more than 0.5, and transmission losses from less than 10dB/km to more than 1000dB/km. Some manufacturers offer bundled fibers in which the individual glass fibers are small enough to allow the cable to be very flexible. In earlier days of fiber optic development, bundled fibers were considered necessary for reliability because breakage of one or more fibers could be tolerated without total loss of signal transmission. Also, the large diameter of the fiber bundle allowed more tolerance in connector alignment. The popularity of fiber bundles has dwindled because the single-fiber cable durability is better than had been anticipated, and connectors are now available which are capable of providing the precise alignment required for low coupling loss with small-diameter single fibers.

Flux Budgeting

Flux requirements for fiber optic systems are established by the characteristics of the receiver noise and bandwidth, coupling losses at connectors, and transmission loss in the cable.

The flux level at the receiver must be high enough that the signal-to-noise ratio (SNR) allows an adequately low probability of error, P_e. In the Hewlett-Packard fiber optic system, the receiver bandwidth and noise properties allow a $P_e < 10^{-9}$ with a receiver input flux of 0.8μW under worst-case conditions. At higher flux levels, the P_e is reduced.

From the receiver flux requirement (for given P_e), the flux which the transmitter must produce is determined from the expression for a point-to-point system:

$$(11)\quad 10 \log \left(\frac{\phi_T}{\phi_R} \right) = \alpha_0 \ell + \alpha_{TC} + \alpha_{CR} + n\alpha_{CC} + \alpha_M$$

where ϕ_T is the flux (in μW) available from the transmitter
- ϕ_R is the flux (in μW) required by the Receiver at P_e
- α_0 is the fiber attenuation constant (dB/km)
- ℓ is the fiber length (km)
- α_{TC} is the Transmitter-to-Fiber coupling loss (dB)
- α_{CC} is the Fiber-to-Fiber loss (dB) for in-line connectors
- n is the number of in-line connectors; n does not include connectors at the transmitter and receiver optical ports
- α_{CR} is the Fiber-to-Receiver coupling loss (dB)
- α_M is the Margin (dB), chosen by the designer, by which the Transmitter flux exceeds the system requirement

Equation (11) is called the FLUX BUDGET and it is represented graphically in Figure 7. The same basic units (watts) are used for flux and for power, so it is correct and convenient to express flux in "dBm".

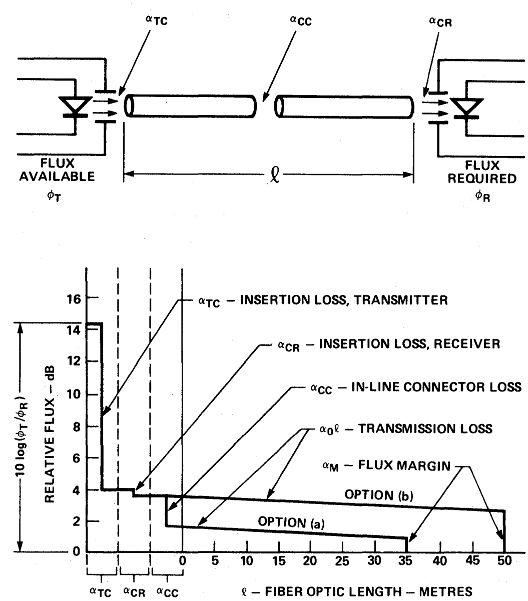


Figure 7. Flux Budget — Graphical Representation.

$$(12)\quad \phi(\text{dBm}) = 10 \log \left(\frac{\phi(\text{mW})}{1 \text{ mW}}\right) = 10 \log \left(\frac{\phi\ (\mu\text{W})}{1000\ \mu\text{W}}\right)$$

Here is an example of how the flux budget works:

1. Transmitter $\phi_T = 44\mu$W
2. Receiver $\phi_R = 1.6\mu$W

$$10 \log \left(\frac{\phi_T}{\phi_R}\right) = 14.39\text{dB}$$

Transmitter optical port: diameter = 200μm, N.A. = 0.5

Optical fiber (in connector): core diam. = 100μm, N.A. = 0.3

3. $\alpha_{TC} = \alpha_A + \alpha_{NA} = 20 \log\left(\frac{200}{100}\right) + 20 \log\left(\frac{0.5}{0.3}\right)$

$= 6.02\text{dB} + 4.44\text{dB} = 10.46\text{dB}$

Receiver optical port: diameter = 200μm, N.A. = 0.5

4. Because the diameter and N.A. of the receiver are both larger than those of the fiber, there is only a small amount of Fresnel loss, making $\alpha_{CR} \approx 0.34$dB

5. Apply equation (11) to see what the flux budget allows:

$$14.39\text{dB} = \alpha_0\ell + 10.46\text{dB} + n\alpha_{CC} + 0.34\text{dB} + \alpha_M$$
$$\alpha_0\ell + n\alpha_{CC} + \alpha_M = (14.39 - 10.46 - 0.34)\text{dB} = 3.59\text{dB}$$

6. Assume a transmission distance of 35 metres at 20dB/km

If cable length selections are 10-, 25-, and 50-metre lengths and connector loss is $\alpha_{CC} = 2dB$, then either of two options may be chosen:

7. a) Use a 10m and 25m length with one connector:
$\alpha_0 \ell + \alpha_{CC}$ = (35m x 0.02dB/m) + 2dB = 2.7dB
This leaves α_M = (3.59 - 2.7)dB = 0.89dB

7. b) Use a 50m length and no connector:
$\alpha_0 \ell$ = (50m x 0.02dB/m) = 1.0dB leaving α_M = 2.59dB

Unless there is some good reason (cost, convenience, etc.) for choosing the 10m/25m option, it would be better to select the 50-metre option because it allows a larger α_M. In flux budgeting, α_M should always be large enough to allow for degradation of the efficiency of the flux generator in the transmitter (LED, IRED, laser, etc.). On the other hand, in dealing with more powerful transmitters, α_M must not be so large that it exceeds the dynamic range of the receiver.

Dynamic Range

The dynamic range of the receiver must be large enough to accommodate all the variables a system may present. For example, if the system flexibility requirement is for transmission distances ranging from 10 metres to 1000 metres with 12.5dB/km cable, and up to two in-line connectors, the dynamic range requirement is:

$$\begin{aligned} \alpha_0 \ell &= 1\text{km} \times 12.5\text{dB/km} = 12.5\text{dB} \\ n\alpha_{CC} &= 2 \times 2\text{dB} = 4.0\text{dB} \\ \alpha_M &= 3.0\text{dB} \\ \text{thermal variations} &= \underline{1.0\text{dB}}\text{(estimated)} \\ & \quad 20.5\text{dB} \end{aligned}$$

Accommodating a 20dB optical power dynamic range plus high sensitivity requires the receiver to have two important features: automatic level control, and a-c coupling or its equivalent. The a-c coupling keeps the output of the amplifier at a fixed quiescent level, relative to the logic thresholds, so that signal excursions as small as the specified minimum can cause the amplifier output to exceed the logic threshold. This function can also be called d-c restoration.

ALC (automatic level control) adjusts the gain of the amplifier. Low-amplitude excursions are amplified at full gain; high-amplitude excursions are amplified at a gain which is automatically reduced enough to prevent saturation of the output amplifier. Saturation affects propagation delay adversely so ALC is needed to allow high speed performance at high, as well as low, signal levels.

HEWLETT-PACKARD'S FIBER OPTIC SYSTEM

A number of objectives were established as targets for this development. Convenience and simplicity of installation and operation were the primary objectives, along with a probability of error $P_e < 10^{-9}$ at 10Mb/s NRZ, over moderate distances. In addition, there were the traditional Hewlett-Packard objectives of rugged construction and reliable performance. Manufacturing costs had to be low enough to make the system attractively priced relative to its performance.

Electrical convenience is provided by several system features. The Receiver and the Transmitter require only a single +5-volt supply. All inputs and outputs function at TTL logic levels. No receiver adjustments are ever necessary because the dynamic range of the Receiver is 21dB or more, accommodating fiber length variations as well as age and thermal affects. When the system is operated in its internally coded mode, it has NRZ (arbitrarily timed data) capability and is no more complicated to operate than a non-inverting logic element. Built-in performance indicators are available in the Receiver; the Link Monitor indicates satisfactory signal conditions and the Test Point allows simple periodic maintenance checks on the system's flux margin.

There are also several optical and mechanical convenience features. The optical ports of the Transmitter and Receiver are well defined by optical fiber stubs built into receptacles that mate with self-aligning connectors. Low-profile packaging and low power dissipation permit the modules to be mounted without heat-sink provision on P.C. boards spaced as close as 12.5mm (0.5 in.).

The internally-coded mode of operation is the simplest way to use the Hewlett-Packard system. This mode places no restriction on the data format as long as either positive or negative pulse duration is not less than the minimum specified. The simplicity is achieved by use of a 3-level coding scheme called a PULSE BI-POLAR (PBP) code. This mode is selected simply by applying a logic low (or grounding) to the Mode Select terminal on the Transmitter — no conditioning signal or adjustment is necessary in the Hewlett-Packard Receiver because it automatically responds to the PBP code.

Transmitter Description

Figure 8 shows symbolically the logical arrangement of the Transmitter, waveforms for the signal currents I_A and I_B, and the resulting waveforms for the output flux. The arrangement shown is logically correct but circuit details are not actually realized as shown. For example, the current sources actually have partial compensation for the negative temperature coefficient of the LED (or IRED). In Figure 8, there are five important things to notice.

First, notice that the bias current, I_C, is never turned off — not even when the Transmitter is operated in the externally coded mode (Mode Select "high"). This is done to enhance the switching speed of the LED (or IRED) in either internally- or externally-coded mode. The bias current also stabilizes the flux excursion ratio (k in Equation 14) symmetry in the internally-coded mode.

Second, notice that

ϕ_L, the low-level flux, is produced by I_C
ϕ_M, the mid-level flux, requires $I_B + I_C$
ϕ_H, the high-level flux, requires $I_A + I_B + I_C$

As far as the Receiver is concerned, the excursion flux, $\Delta\phi$, produced by switching I_A and I_B, is the important parameter of the Transmitter. Average flux is, of course, related to excursion flux but is not as important in establishing the SNR of the system.

Third, notice that with Mode Select "low" and a 500kHz signal at Data Input, there will be only one refresh pulse generated in each logic state. The excursions (ϕ_H-ϕ_M) and (ϕ_M-ϕ_L) are nearly balanced so an average-reading flux meter will indicate the mid-level flux, ϕ_M, within +0.6% or -0.6% depending on whether the flux excursion ratio, k, is at its maximum or at its minimum limit.

APPLICATION NOTES

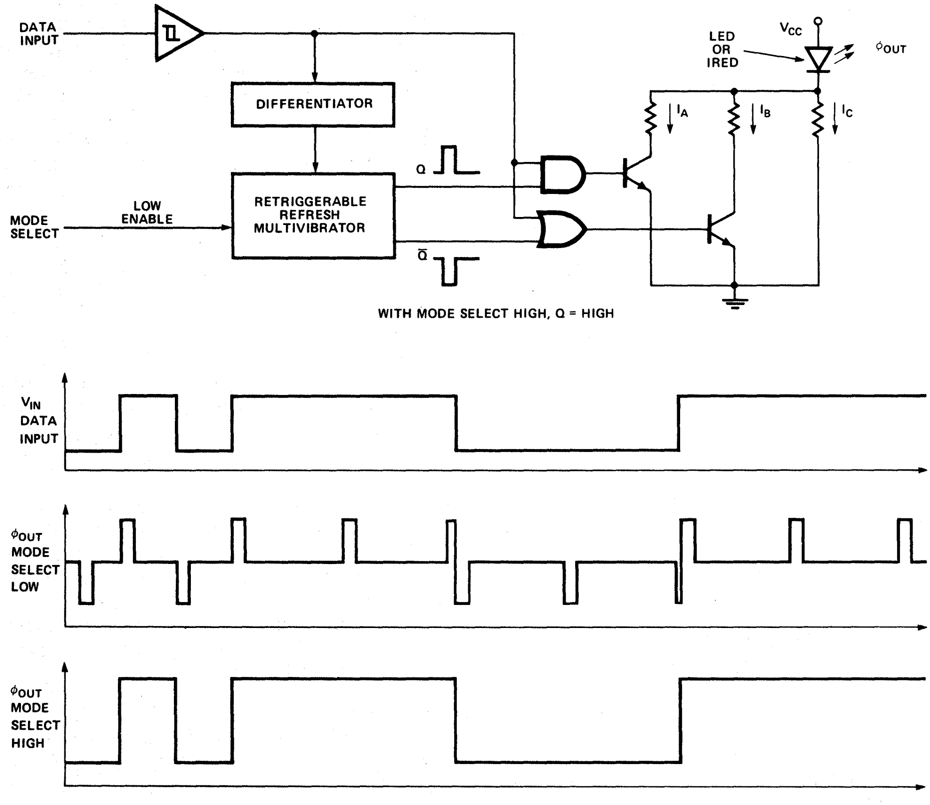


Figure 8. Transmitter Block Diagram and Waveforms.

Fourth, notice that, with Mode Select "low", any Data Input transition (either H-L or L-H) retriggers the Refresh Multivibrator to start a new train of pulses. All refresh pulses for either logic state have the same duration. This keeps the average flux very near the mid-level even when the duration in either logic state of arbitrarily timed input data is very short. Notice also that any refresh pulse is overridden (abbreviated) by the occurrence of a Data Input transition so there is no additional jitter when the duration of the Data Input in either state is at or near the same length of time as the refresh interval. The refresh interval is very long, relative to the refresh pulse duration, making a duty factor of approximately 2%; this also is done to keep the average flux near mid-level regardless of how long Data Input remains in either logic state. The only condition under which the average flux can deviate significantly from the mid-level occurs when Data Input remains in one state for a period of time LESS than the duration of the refresh pulse. If this is likely to occur, the format should be configured so the numbers of 1's and 0's are balanced as they would be in Manchester code. Observing this data format allows the use of the internally-coded mode of the Hewlett-Packard system at data rates ranging from arbitrarily low to higher than 10M Baud, with the absolute limit being that at which the signal intervals become as short as t_{PHL} and/or t_{PLH}.

Fifth, notice that with Mode Select "high," the Q output of the Refresh Multivibrator is "high" (and $\overline{Q}$ is "low"). Under this condition, I_A and I_B are both ON when Data Input is "high" and both OFF when it is "low". This makes the output flux excursion a logical replica of the Data Input.

Flux Measurement

A high-speed photodetector and oscilloscope could be used for measuring the excursion flux, but an average-reading flux meter can be used to measure $\Delta\phi$ as follows:

With Mode Select "high":

1. Apply steady-state "low" to Data Input and observe ϕ_L with flux meter.
2. Apply a 500kHz square wave (50% duty factor) to Data Input and observe $(\Delta\phi + \phi_L)$ with the flux meter and subtract ϕ_L (Step 1) to obtain $\Delta\phi$.

This procedure also yields the proper value of the high-level flux, ϕ_H, to be used in computing the flux excursion ratio, k. Since $\phi_H = (\phi_L + 2\Delta\phi)$, the value of ϕ_H is:

(13) HIGH-LEVEL FLUX, $\phi_H = \underbrace{2(\Delta\phi + \phi_L)}_{\text{Step 2}} - \underbrace{(\phi\ )}_{\text{Step 1}}$

It appears, from the waveforms in Figure 8, that the 500kHz signal prescribed in Step 2 is not necessary; that is, with Data Input at a steady-state high, the flux meter would read ϕ_H directly, from which $\Delta\phi$ could be calculated by subtracting ϕ_L (observed in Step 1) and dividing by two. However, this method would cause slightly more heating of the LED and lead to a slightly different (and incorrect) measurement of ϕ_H and $\Delta\phi$. With the values of ϕ_H and ϕ_L from Step 1 and 2, the flux excursion ratio can now be computed:

(14) FLUX EXCURSION RATIO, $k = \dfrac{\phi_H - \phi_M}{\phi_M - \phi_L}$

In a 2-Level Code, there is, of course, no mid-level; however, the definition of flux excursion ratio is the same as for Pulse Bi-Polar code, i.e., Equation (14). It is only necessary to substitute average flux for mid-level flux, ϕ_M, in Equation (14). For 2-Level Code, the average flux is:

(15) AVERAGE FLUX (2-Level Code) $= \dfrac{\phi_H \Sigma t_H + \phi_L \Sigma t_L}{\Sigma t_H + \Sigma t_L}$

where Σt_H is the total time the flux is at level ϕ_H
Σt_L is the total time the flux is at level ϕ_L

Substitution of this expression for ϕ_M in Equation (14) leads to:

(16) FLUX EXCURSION RATIO $= k = \dfrac{\Sigma t_L}{\Sigma t_H}$

Equation (16) shows why it is that when a 2-Level Code is used (e.g., with Mode-Select "high" in the Hewlett-Packard Transmitter) the data input signal must, on average, have a 50% duty factor to make $k = 1$. That is, in the averaging interval, the total number of "mark" intervals should be equal to the total number of "space" intervals, such as in Manchester code.

Use of 2-Level Code also requires that the input flux remain for less than 5μs at either high or low level. This is necessary to avoid "pulling" the receiver dc restorer voltage too far away from the value corresponding to the average flux, and possibly losing occasional bits.

Receiver Description

The Hewlett-Packard Receiver block diagram is shown in Figure 9. There are four functional blocks:

1. The amplifier, including a gain-control stage and split-phase outputs with a voltage divider for each.
2. The dc-restorer with a long time constant.
3. Logic comparators with an R-S latch.
4. Positive and negative peak comparator with single-ended output for the ALC and link monitor circuits.

Optical flux at the input is converted by the PIN photodiode to a photocurrent, I_P, which is converted to a voltage by the PREAMPLIFIER. This voltage is amplified to a positive-going output, V_{P1}, and a negative-going output, V_{N1}. A rising input flux will cause V_{P1} to rise and V_{N1} to fall. These voltages are applied to the differential inputs of the DC RESTORER AMPLIFIER whose output, V_T, falls until it is low enough to draw the average photocurrent away from the preamplifier via the 25k resistor. This makes $V_{P1} \approx V_{N1}$ when the input flux is at the average level. The output impedance of the dc restorer amplifier is very high, making a long time constant with the filter capacitor, C_T. The long time constant is required for loop stability when input flux levels are so low that there is little or no ALC gain reduction, with consequently high loop gain. With no input flux, $V_T = V_{TMAX}$; as input flux rises, V_T falls proportionately, so the voltage at the TEST POINT can be used as an indicator of the average input

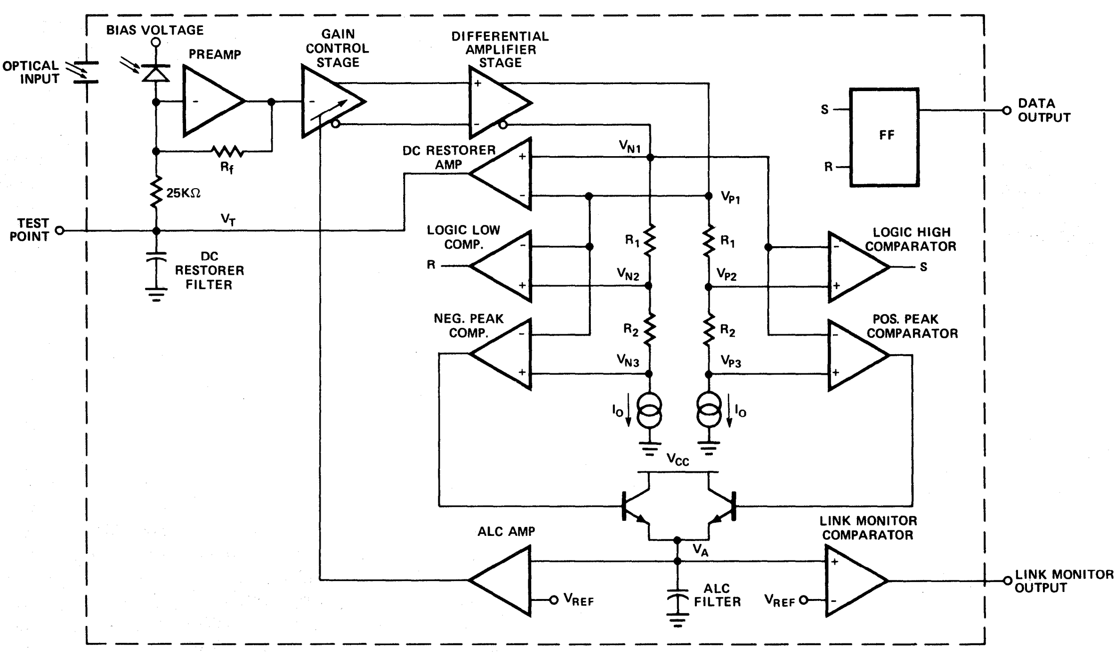


Figure 9. Receiver Block Diagram.

flux. With respect to the Receiver optical port, the responsivity of the PIN photodiode is approximately 0.4A/W, leading to the expression:

$$\text{(17) AVERAGE INPUT FLUX}, \phi_{AV}(\mu W) \approx \frac{[V_{TMAX} - V_T]\ (mV)}{10}$$

where V_{TMAX} = Test Point Voltage with no optical input signal.

The instrument for observing V_T must not load the Test Point significantly, so an input resistance of 10MΩ is recommended.

As described above, when the input flux is at the average level, the positive-going and negative-going output voltages V_{P1} and V_{N1} are approximately equal. Notice that this makes the outputs of both logic comparators low. A positive flux excursion, rising faster than the dc restorer (with its long time constant) can follow, will cause V_{P1} to rise and V_{N1} to fall. If the positive flux excursion is high enough, the LOGIC HIGH COMPARATOR input voltage (V_{P2} - V_{N1}) becomes positive, and a SET pulse is produced for the R-S flip-flop. [Similarly, a negative flux excursion of such amplitude would make (V_{N2} - V_{P1}) become positive and a RESET pulse would be produced.] A larger amplitude of positive flux excursion would make the POSITIVE PEAK DETECTOR input voltage (V_{P3} - V_{N1}) change from negative to positive and cause current to flow into the ALC FILTER capacitor. When the voltage V_A starts to rise above V_{REF}, the ALC AMPLIFIER output will operate on the GAIN CONTROL AMPLIFIER to limit the Receiver's forward gain. Notice that the ALC action is the same for a negative flux excursion, so that the Receiver's gain limitation is determined EITHER by positive flux excursion OR by negative flux excursion — whichever is the larger. For this reason, the positive and negative excursions must be nearly balanced with respect to the average flux. The allowable imbalance is determined by the values of the resistors in the negative and positive voltage dividers. The ALC action limits the maximum excursion to a voltage I_O (R_1 + R_2), whereas the logic threshold is only I_O R_1. Actual limits are established by the tolerances on the resistors and current sources. Notice that the ALC voltage, V_A, activates both the ALC COMPARATOR and the LINK MONITOR COMPARATOR. Therefore, a "high" LINK MONITOR signifies two conditions:

1. The input flux excursions are high enough to cause ALC action (gain limitation).
2. The excursions are more than adequate for operation of the logic comparator.

Notice that the LINK MONITOR could be "high," but k could be outside the specified limits such that P_e exceeds 10^{-9}. Conversely, because of safety margin in the Receiver design, it is also possible to have $P_e < 10^{-9}$ when the flux excursions are too small to make the LINK MONITOR "high".

OPERATION OF THE HEWLETT-PACKARD SYSTEM

With Hewlett-Packard Components Exclusively

The main concern in a fiber optic link is the flux budget. Other areas of concern are: data rate, data format, and the interface with other elements of a data transmission system.

Flux budgeting, using the Hewlett-Packard Transmitter, Receiver, Connector, and Cable components is very straightforward for most applications. It is necessary only to use the data sheet information correctly in making the coupling loss and transmission loss allowances.

When used with other Hewlett-Packard components, the characteristics of the Receivers are not critical. Their optical ports have a diameter and N.A. which are both greater than the size and N.A. of the Hewlett-Packard Cable. The Receivers also have a high responsivity and the spectral response is nearly constant over the spectrums radiated by Hewlett-Packard Transmitters.

With Components From Other Manufacturers

When using the Hewlett-Packard Receivers with other cables, it may be necessary to account for N.A. loss and/or area mismatch loss. When other sources are used, it may be necessary to compute an effective flux ratio:

$$\text{(18) EFFECTIVE FLUX RATIO, } EFR_S = \frac{\int \phi_\lambda R_{r\lambda} d_\lambda}{\int \phi_\lambda d_\lambda} \quad \text{(Source Spectrum)}$$

where $R_{r\lambda}$ is the relative response of the Receiver (from data sheet)

ϕ_λ is the spectral flux function of the source

If the transmission loss of the cable varies sharply over the wavelength range of the source spectrum, then the spectral transmittance of the cable should be included in the computation of EFR. The spectral transmittance varies with cable length, so the integration must be performed using the cable length required in a particular installation:

$$\text{(19) EFFECTIVE FLUX RATIO, } EFR_{CS} = \frac{\int \tau_\lambda \phi_\lambda R_{r\lambda} d_\lambda}{\int \tau_\lambda \phi_\lambda d_\lambda} \quad \text{(Cable and Source)}$$

where τ_λ is the spectral transmittance of a particular length of fiber optic cable, computed as:

$$\text{(20)} \quad \tau_\lambda = 10^{-\left(\frac{\ell}{10}\right)\alpha_{0\lambda}}$$

where $\alpha_{0\lambda}$ is the spectral function in (dB/km) of the fiber optic cable and ℓ is the particular cable length (km)

Notice that as the length is reduced, τ_λ becomes more nearly a constant and may be factored out of both numerator and denominator of Equation (19). When EFR is significantly less than unity, it enters the flux budget expression, Equation (11).

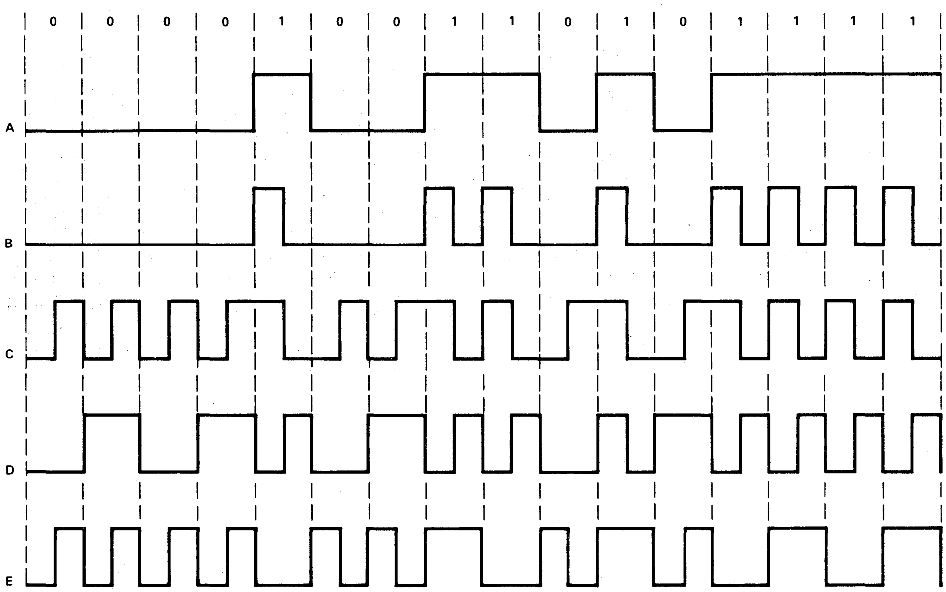
$$\text{(21)} \quad 10 \log\left(\frac{\phi_T}{\phi_R}\right) = \alpha_{TC} + \alpha_{CR} + n\alpha_{CC} + \alpha_0 \ell + \alpha_M - 10 \log (EFR)$$

See Equations 11, 18, and 19 for definition of terms.

The optical ports of Hewlett-Packard Transmitters are designed for mating with Hewlett-Packard Cable/Connector assemblies, but their characteristics require a little more attention than do the Receiver optical ports. The Transmitter and Cable/Connector data sheets should be consulted for the correct values of size and N.A., or for the directly-given value of transmitter-to-fiber coupling loss, α_{TC}, to use in flux budgeting. In applications having very short transmission distances, but requiring a number of in-line (cable-to-cable) connections, it is likely to be advantageous to use fiber optics of larger core diameter and N.A., such as some of the plastic types. The larger core diameter reduces the likelihood of losses in connectors due to misalignment. Depending on the size and N.A. of the Transmitter optical port, a larger core diameter and N.A. in the fiber optic cable may also reduce α_{TC}, but if the cable core diameter is too large, the cable-to-receiver loss, α_{CR}, may be excessive.

Data Rate and Format

The other areas of concern (data rate, data format, and interface) are interactive, depending on system requirements. In any single transmitter-to-receiver link, the flux budget along with probability of error P_e, establish the signaling rate, in baud units, while the data rate, in bits per second, depends also on the data format, or transmission code. NRZ (Non-Return-to-Zero) is the term for a transmission code in which the signal does not periodically return to zero. If a stream of NRZ data contains a series of consecutive "1's", the signal remains at the "1" level; similarly, the signal remains at the "0" level for consecutive "0's". With RZ (Return-to-Zero) codes, the level periodically changes from high level to low level or back, never remaining at either level for a period of time longer than one bit interval. Some examples of codes are given in Figure 10. Notice that NRZ code uses the channel capacity most efficiently since it requires only one code interval per bit interval. The RZ codes illustrated use two code intervals per bit interval while other codes may require an even higher channel capacity for a given data rate. NRZ code requires a clock signal at the receiving end to define, for each interval, the point in time at which the data is valid. The time at which the data is clocked must be sufficiently clear of the interval edges to avoid phase-shift errors due to jitter, rise time, or propagation delay. Since the clock signal is separately transmitted, phase shift in the clock channel can contribute to the phase-shift error unless it is equal, in direction and magnitude, to the phase shift in the data channel. For this reason, fiber optic



	CODE	DESCRIPTION	CHANNEL REQUIRED	REQUIRES DC?	REQUIRES CLOCK?
A	NON-RETURN TO ZERO (NRZ)	High during entire "mark", low during entire "space" interval	1 Mbaud per Mb/s	YES	YES
B	RETURN TO ZERO (RZ)	Low during entire "space", momentarily high during "mark" interval	2 Mbaud per Mb/s	NO	YES
C	MANCHESTER (SELF-CLOCKING RZ)	Positive transition for "space", negative transition for "mark"	2 Mbaud per Mb/s	NO	NO
D	BIPHASE MARK (MANCHESTER II)	Each bit period begins with a transition. "Space" has NO transition during bit period — "mark" has one transition during bit period	2 Mbaud per Mb/s	NO	NO
E	BIPHASE SPACE	Same as Biphase Mark except "mark" and "space" reversed	2 Mbaud per Mb/s	NO	NO

NOTE THAT C, D, E HAVE 50% DUTY FACTOR (k = 1.00)

Figure 10. Examples of NRZ and RZ Code Patterns.

channels carrying clock signals should use the same type of cable and the same length, unless the transmission distance is very short. Note that the transmission time delay in an optical fiber depends on the core index of refraction:

(22) TRANSMISSION DELAY, $t_{\ell} = \left(\frac{1}{c}\right) \ell n$

where c is the velocity of light in a vacuum, $c = 3 \times 10^8$ m/s
ℓ is the fiber optic cable length (m)
n is the core index of refraction

and differential delay between a data channel and a clock channel is:

(23) DIFFERENTIAL DELAY, $t = \left(\frac{1}{c}\right) [\ell_2 n_2 - \ell_1 n_1]$

Some RZ codes are self-clocking — i.e., a separate channel to transmit the clock signal is not required, so there is no problem with differential delay. For this reason, RZ codes may be preferred even though the data rate is less than that of NRZ. Note that in its internally coded mode, the Hewlett-Packard fiber optic system transmits either NRZ or RZ codes of arbitrary format and duty factor. In the externally coded mode, the system requires the code to be RZ; moreover, the duty factor of the code must be 50% and the signal must remain LESS than 5μs in either high state or low state.

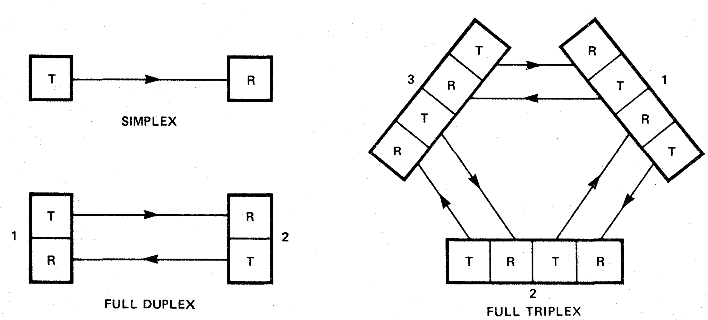
The Hewlett-Packard system is capable of a 10 Mbaud signaling rate. If a higher data rate is required, the data stream can be divided among additional channels. If each channel is RZ coded, such as with Manchester code, the capacity of each channel is 5Mb/s and if the total data rate requirement is 20Mb/s, four channels are required. Using NRZ, the 20Mb/s data can be transmitted on two channels, with a third channel for the clock signal. Thus, if the data rate requirement exceeds 15Mb/s, the NRZ format requires fewer fiber optic channels.

System Configuration

The simplex arrangement in Figure 11 allows data in one direction only, and the format should, therefore, include error checks, such as parity bits. The full duplex arrangement requires two Transmitter/Receiver (T/R) pairs and two cables but allows data to go in both directions simultaneously. If, at a given time, Station 1 is transmitting, the return transmission from Station 2 can be unrelated to the information from Station 1, but could also be a relay or re-transmission of the data received by Station 2, so a logic delay and comparator circuit in Station 1 can check for errors and allow corrections. The same is true for the full triplex arrangement. Extension to larger numbers of stations is possible and the benefits are the same, but the number of T/R pairs increase rapidly, as shown by the series in Figure 11, requiring n (n-1) T/R pairs for n stations.

Half-duplex (not illustrated) is a means for allowing two stations to alternately use the same transmission medium. With a wire cable, half-duplex operation is commonly and easily done; it can also be done with fiber optic cable but the fiber-furcating couplers for accomplishing it are very lossy, are not commonly available, and will not be discussed.

Data interchange among a large number of stations can be accomplished with fewer T/R pairs by using the Master Station Multiplex (MSM) arrangement in Figure 12. The MSM arrangement requires only 2(n-1) T/R pairs for n stations (master + (n-1) slaves). Its operation differs from the full n-plex arrangement of Figure 11 in that only the master station transmits directly to all other stations. Data from any slave station is transmitted to master and re-transmitted to all slave stations according to the "re-transmit enable" ($E_1 \ldots E_X$) selection made in the master station. Thus, a complete error check is possible. Regardless of how many slave stations are added, the transmission delay from any slave to any other slave is just the delay of two fiber optic links plus the propagation



NO. OF STATIONS	NO. OF T/R PAIRS
2	2
3	6
4	12
5	20
n	n(n-1)

Figure 11. Simplex, Full-Duplex, Full Triplex, Full-n-plex Fiber Optic Links.

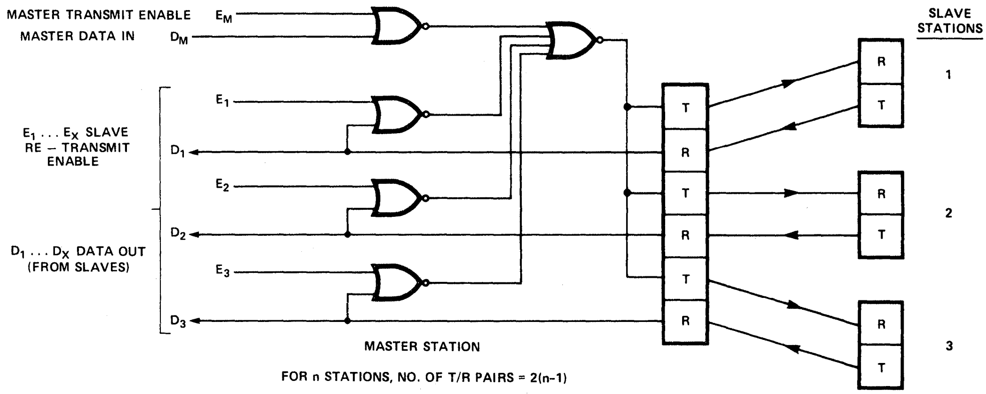


Figure 12. Master Station Multiplex Arrangement for Fiber Optic Links.

delay in the master station's relay circuit. The time delay between re-transmission from the master and the error-check return transmissions from the slaves is the same if each link length is the same, i.e., two links plus relay time. Notice that a complete error check requires an error check in the master, plus an error check in the station where the data originated. Another feature of the MSM system is that any slave station can be disconnected or turned off without affecting the other stations. With slightly more complicated relay control logic in the master stations, the MSM system can provide even more flexibility in the control of data movement — the schematic in Figure 12 is intended only to illustrate the potential flexibility of MSM.

At the expense of less flexibility and longer transmission delay, multiplex operation can be done with an even smaller number of T/R pairs by means of Looped-Station Multiplexing (LSM) as in Figure 13. In addition to requiring only n T/R pairs for n stations, LSM offers the advantage that an error check is required only at the station from which the data originates. There are some disadvantages. A relatively minor disadvantage is the data delay around the loop to where the data originated. A less minor disadvantage is the fact that, even if one of the stations in the loop is designated for loop control, it does not have control as absolute as that of the master station in MSM. A major disadvantage is that removal of one or more stations from the loop may require a re-run of the fiber optic cable unless the flux budget allows insertion of a connector to replace the station(s) removed. There is some error accumulation around the loop, but this is not a disadvantage if error correction is applied.

Error Accumulation

Where error correction is inconvenient or impossible, the accumulation of error through data relay units may be significant. With Hewlett-Packard components operated within the limits prescribed by the data sheet parameters and the flux budget, any point-to-point link has a

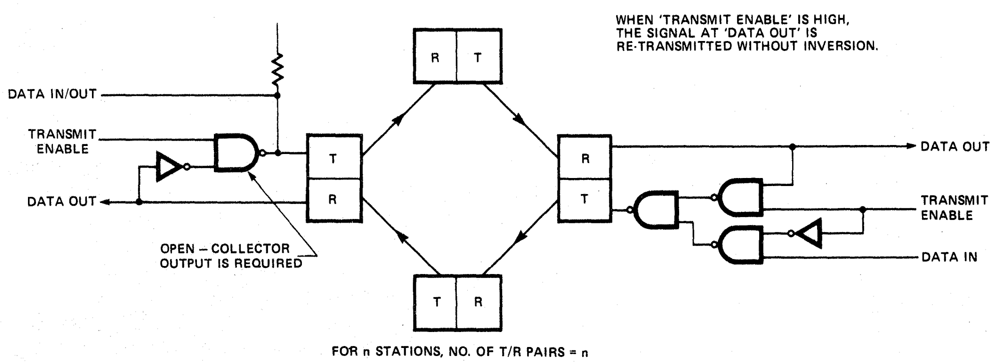


Figure 13. Looped-Stations Multiplex Arrangement for Fiber Optic Links.

probability of error $P_e < 10^{-9}$. This means that $P_e < 10^{-9}$ as long as the loss margin, α_M(dB) is above zero. With a number, n, of repeater links, the worst case estimate of cumulative probability of error is the RMS value:

(24) CUMULATIVE PROBABILITY OF ERROR, $$P_{e,n} = 1 - \prod_{i=1}^{n}(1 - P_{e,i}) \approx \sum_{i=1}^{n} P_{e,i}$$

where $P_{e,i}$ is the probability of error in link "i"

If each link has the same probability of error, P_e, then the cumulative value of P_e is estimated at:

(25) CUMULATIVE PROBABILITY OF ERROR FOR EQUAL P_e's $$P_{e,n} \approx nP_e$$

However, as in any chain, the probability of error is usually just that of the "weakest link," that is, the link having the highest probability of error.

Measuring the probability of error can be very time-consuming if P_e has a very low value. For instance, if $P_e = 10^{-9}$ at 10 Mbaud (BER $= 10^{-9}$), this suggests that if the system is operated for 100 seconds at 10 Mbaud (accumulate 10^9 bits) with one error, the $P_e = 10^{-9}$ is verified. This is not necessarily true. The significance of $P_e = 10^{-9}$ is that over several such periods the average error is one per 100 seconds. A less time-consuming procedure is to lower the signal (flux) level until the error rate, $P_{e,N}$ is measurably high in a comfortable period of time, and note this flux level as ϕ_N, the Noise measurement flux level. The operating flux level is designated ϕ_0, and is found from the ratio:

26. $$\frac{X_0}{X_N} = \frac{\phi_0}{\phi_N} \text{ and } X_0 = X_N \frac{\phi_0}{\phi_N}$$

and from the complementary error function:

$P_e = \text{erfc}(X_0) = 1 - \text{erf}(X_0)$ calculated for ϕ_0
$P_{e,N} = \text{erfc}(X_N) = 1 - \text{erf}(X_N)$ measured at ϕ_N

$$\text{erfc}(X) \approx \frac{.54}{X}(\epsilon^{-X^2}) \text{ for } P_e < 10^{-4}$$

This measurement and relationship can be useful in evaluating the relative merits in the tradeoff between running a single link over a long distance versus operating with one or more repeaters. The use of repeaters usually yields the lower P_e, but may be "overkill" in some cases.

INSTALLATION, MEASUREMENT, AND MAINTENANCE

The shielded metal packages of Hewlett-Packard Fiber Optic Modules are very sturdy and can be mounted in any position. Both Transmitter and Receiver dissipate very low power, so heat sinking is not required. A cool location is preferred, especially for the Transmitter. The main concern in selecting the locations of both modules is accessibility of the optical ports.

Mounting

The preferred mounting is with two #2-56 screws on a printed circuit board. Clearance must be provided for the Lock Nut, which protrudes 0.5mm to 1.0mm (depending on angular position) beyond the plane of the module's bottom surface. The usual way to deal with this is to allow the Lock Nut to overhang the edge of the P.C. board as in Figure 14. Lock Nut clearance could also be provided by an opening in the board, or by using washers of 1mm thickness on the #2-56 mounting screws to space the Module bottom 1mm from the board. Screws entering the #2-56 tapped holes MUST NOT TOUCH BOTTOM AS THIS MAY DAMAGE THE MODULE. The #2-56 tapped hole is 5.6mm (0.22 in.) deep, which provides an ample purchase on the thread.

P.C. Board Thickness		Recommended Screw Length — mm (in.)	
mm	**in.**	**W/O Spacer**	**W/1-mm Spacer**
0.79	1/32	4.78 (.188)	6.35 (.250)
1.59	1/16	6.35 (.250)	6.35 (.250)
2.38	3/32	6.35 (.250)	6.35 (.250)

The #2-56 holes near the front of the package are the only screw holes that may be used for mounting the module. UNDER NO CIRCUMSTANCES MAY THE SCREWS ALREADY INSTALLED OR THE SET SCREW BE DISTURBED. Disturbing these may cause interior damage.

For additional support, the electrical leads may be bent down and soldered into the P.C. board. In bending the leads, care must be taken to avoid strain at the point where the leads enter the glass seal. This can be done by applying mechanical support between the module and the bending point which should be at least 1.0mm (0.04 in.) from the end of the module. A needle-nose pliers can also be used to bend the leads individually, providing no bending moment is transferred to the seal. See Figure 14 for details fo these techniques.

Panel mounting can also be used. This is an especially attractive mounting when R.F. shield integrity must be maintained. As seen in Figure 15, the panel thickness must be less than 4mm (5/32 in.) and have a counter-bore to receive the Lock Nut. This will make the mounting secure and leave enough of the Barrel outside the panel to permit installation of an external mounting nut as well as the Cable Connector.

Fiber Optic Cable Connections

The data sheet cautions against disturbing the Lock Nut and Barrel. This is to prevent damage by someone who has not read the following material:

As seen in Figure 16, there is a clearance between the interior end of the Barrel and a shoulder on the Fiber Alignment Sleeve. If this clearance is not maintained, there is a risk that a force applied to the Barrel may be transmitted by the Fiber Alignment Sleeve to the optical fiber stub, forcing the stub against the face of the source or detector. The source (or detector) is an extremely fragile semiconductor device and even a very small force can cause severe damage. Should it be necessary to remove the Lock Nut and Barrel, they should be reinstalled with this procedure:

1. Lightly and carefully thread the Barrel into the Module body until it comes against the shoulder of the Fiber Alignment Sleeve.
2. Back the Barrel OUT ONE FULL TURN, then HOLD THE BARREL FROM TURNING while seating the Lock Nut securely against the body. During final tightening of the Lock Nut, the Barrel may be allowed to enter no more than HALF A TURN.

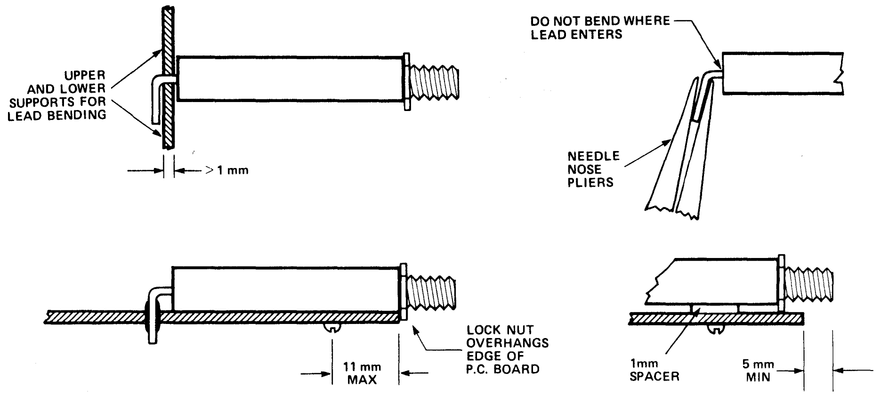


Figure 14. Lead Bending and P.C. Board Mounting.

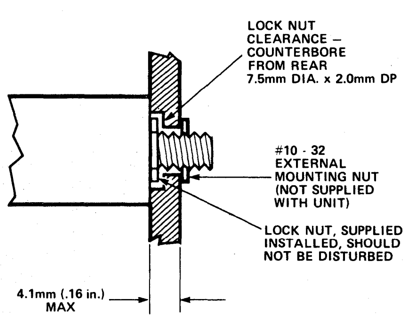


Figure 15. Panel Mounting.

When Hewlett-Packard Cable Connectors are joined, either to each other or to the optical port of a Transmitter or Receiver, there is a cylindrical spring Sleeve that aligns the Ferrules. This is shown in Figures 16 and 17. It may be difficult to see, but the Sleeve does have a slightly flattened "leaf" on either side of a notch. The notch makes the leaves spring separately, allowing the Ferrules at opposite ends of the sleeve to have slightly different diameters and yet be firmly aligned by the curved interior wall. A chamfer on the edge of the Ferrule aids insertion. In making temporary Cable-to-Cable connection, it is permissible, and often convenient, to omit the Barrel, since it does not perform an alignment function. When the Barrel is used for a more sturdy joint, the connection procedure is:

1. Install the Sleeve and Barrel on one Connector, using only FINGER TIGHTNESS of the Coupling on the Barrel.
2. Start the Ferrule of the second Connector into the Sleeve.
3. Engage the Coupling on the Barrel threads and tighten FINGER TIGHT.

Alignment of the Ferrules (and hence the fiber optics) is performed by the Sleeve; the Barrel and Couplings are intended only for tensile support, but if they are OVER tightened, they may cause misalignment. Loss of coupling due to misalignment can be observed at the V_T (Test Point) on the Receiver when the System is active: $\Delta V_T/\Delta\phi \approx 10 mV/\mu W$.

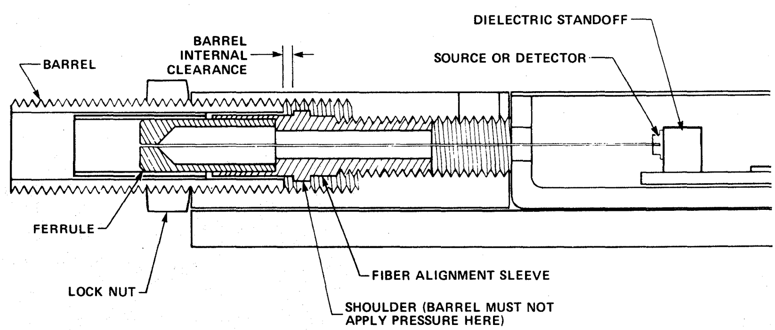


Figure 16. Opto-Mechanical Structure of T/R Modules.

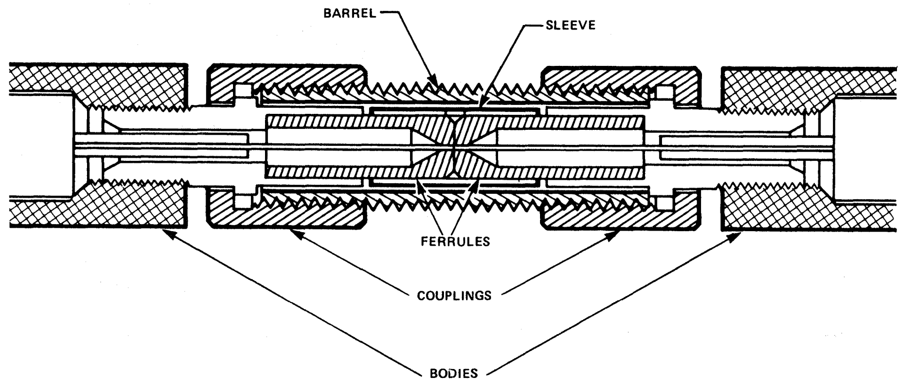


Figure 17. In-Line Connector Arrangement.

The procedure above applies also to making Cable connection at the Receiver and Transmitter, except that the Sleeve and Barrel are already installed. In manufacture, the Sleeve in the Module is pre-stressed for a tighter fit on the Ferrule in the Module than on the Ferrule in the Connector. The Sleeve is not likely to be pulled out when the Module is disconnected, but if that does happen, it can be reinstalled without removing the Barrel by using the Connector Ferrule to guide and support it.

In connecting fiber optics other than those from Hewlett-Packard to a Hewlett-Packard module, it is necessary to center the fiber in a cylinder with the same outside diameter as the Hewlett-Packard Ferrule over a length (to first shoulder) equal to half the length of the Sleeve, i.e., 3.5mm. This is adequate for a temporary connection. For a more permanent connection, add a coupling to fit the #10-32 thread on the Barrel.

Power Supply Requirements

Power supply lines for the Transmitter and the Receiver should each have a pi filter of two 60μF shunt capacitors and a 2.2μH (<1Ω) inductor. The Transmitter needs this filter to prevent transients from reaching other equipment when the LED (or IRED) currents are switched. The Receiver needs the filter to keep line transients from interfering with its extremely sensitive amplifier. In addition, the Receiver may need its own regulator, as shown in the data sheet, to prevent low-frequency transients or ripple from interfering with the data stream. If a regulator is used, the pi filter should be between the regulator output and the Receiver supply terminal. The Transmitter needs no regulator if the supply voltage is in the specified range.

System Performance Evaluation

System performance checks may be done by using error-detection equipment, such as the Hewlett-Packard Mod. 3760A Word Generator and 3761 Error Detector as indicated in Figure 18. The Mod. 3780A Pattern Generator/Error Detector which contains both word generator and error detector is also usable, although it has less flexibility in word generation and a lower data rate capability. These instruments have low-impedance (50Ω and 75Ω) inputs and outputs. The outputs have adequate voltage swing to drive the Fiber Optic Transmitter Data Input, but ringing may occur unless the signal line is properly terminated. The low-impedance inputs require a buffer amplifier between the Receiver output and the Error Detector input. Here also the voltage swing is ample, so a simple emitter follower will do as a buffer.

With Mode Select "low" (on the Fiber Optic Transmitter), the Word Generator may be set for either NRZ or RZ code, and there is no restriction of any kind on word length or composition (pseudo random or selected). With Mode Select "high", the code selection can be either NRZ or RZ but in either code the word composition must be such that:

1. No interval > 5μs of consecutive marks or consecutive spaces
2. Duty factor: $.44 < DF < .57$ or $.75 < k < 1.25$

The first condition can be examined with an oscilloscope, but if word length is such that:

$$\frac{\text{word length (bits)}}{\text{data rate (bits/second)}} < 5 \text{ microseconds}$$

then there is no way that any consecutive marks or spaces can extend over 5μs.

The easiest way to check duty factor is by observing k directly on an ac coupled oscilloscope: first establish the baseline position (e.g., center of scope face) with zero signal input, then with the data signal applied:

$$k = \frac{\text{excursion above baseline position}}{\text{excursion below baseline position}}$$

where the oscilloscope deflects upward for positive input. For this observation, the oscilloscope need not be synchronized — it could be free-running. The word composition should be adjusted to bring k within the specified limits. The word composition can be adjusted by adding zeroes, changing word length, or by handselecting the bit sequence.

Either error detector has two modes of operation: BER (Bit Error Rate) mode and "count" mode. The count mode is simplest to use and gives an earlier indication of the result of any system adjustment.

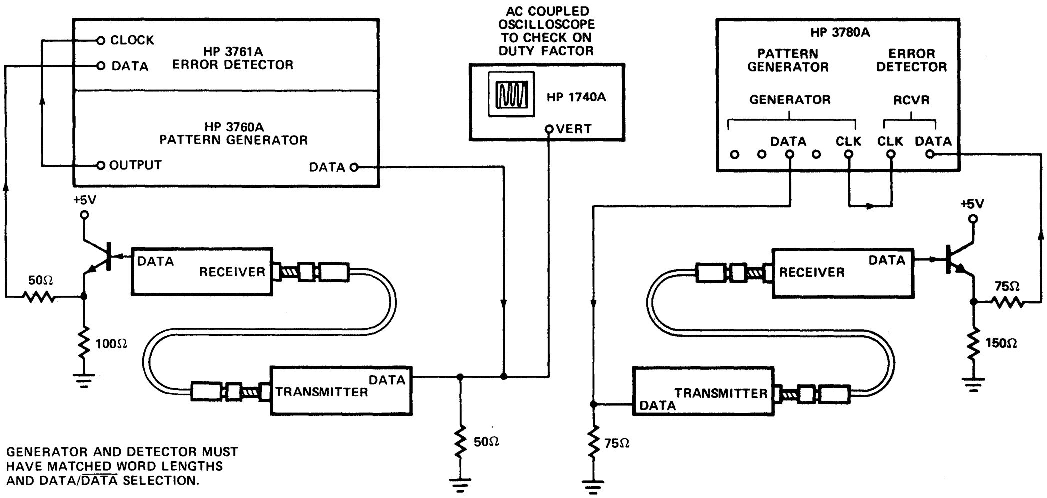


Figure 18. Bit Error Rate Measurement Arrangement.

With the System at normal operating flux level, the error rate is so low that it would take several hours or even days to make an accurate BER measurement. If the flux level is reduced, SNR falls and BER rises until it becomes measurable. Then the error function [see Equation (26)] can be applied to determine the BER at the normal flux level in terms of the ratio ϕ_O/ϕ_N where ϕ_O is the operating flux level and ϕ_N is the flux at the reduced level where the BER was measured. The problem now is that ϕ_N may be too low to measure with equipment at hand. The solution is in the Receiver Test Point voltage, V_T, which varies linearly as Receiver input flux — see Equation (17). But even this method has limits; when the flux becomes a small fraction of a microwatt, the voltage difference ($V_{TMAX} - V_T$) cannot be accurately observed. The solution to this problem is in the Transmitter-to-Cable connection. Just back off the Coupling, noting the number of turns while observing V_T, then plot a curve like that of Figure 19. The curve is quite repeatable if care is taken to avoid backlash and rotation of the Connector Body (rotate Coupling only) but the curve is not the same for each System.

Operating Margin Measurement

The flux budget margin, α_M, for a given P_e can be found using the Connector on the Transmitter as an adjustable attenuator as described above, proceeding as follows:

1. Prepare a curve similar to Figure 19.
2. Count the turns, N, needed to get measurable error, $P_{e,N}$.
3. Find α_N(dB) from N and the curve from Step 1.
4. Find X_N from erfc (X_N) = $P_{e,N}$ (measured).
5. Find X_0 from erfc (X_0) = P_e (given).

(27) $\alpha_M(\text{dB}) = \alpha_N - 10 \log \frac{X_0}{X_N}$ FOR GIVEN P_e

Absolute flux levels at "N" turns can be found by measuring the flux level when N = 0 and applying a ratio. A rough measurement can be made using the Test Point voltage, V_T, and Equation (15). A more precise measurement requires a calibrated radiometer, such as the EG&G Mod. 550, used as shown in Figure 20a. With its "flat" filter installed, the EG&G Mod. 550 reads the radiant

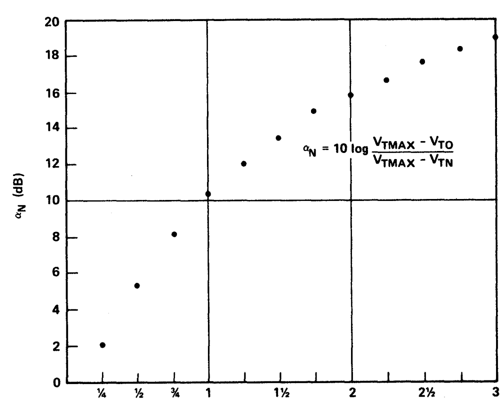
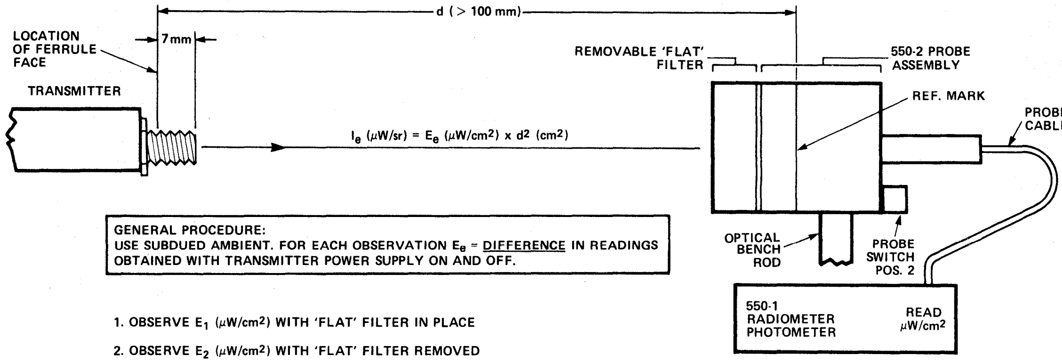


Figure 19. Flux Decoupling by Rotation of Connector Coupling.

APPLICATION NOTES



GENERAL PROCEDURE:
USE SUBDUED AMBIENT. FOR EACH OBSERVATION E_e = DIFFERENCE IN READINGS OBTAINED WITH TRANSMITTER POWER SUPPLY ON AND OFF.

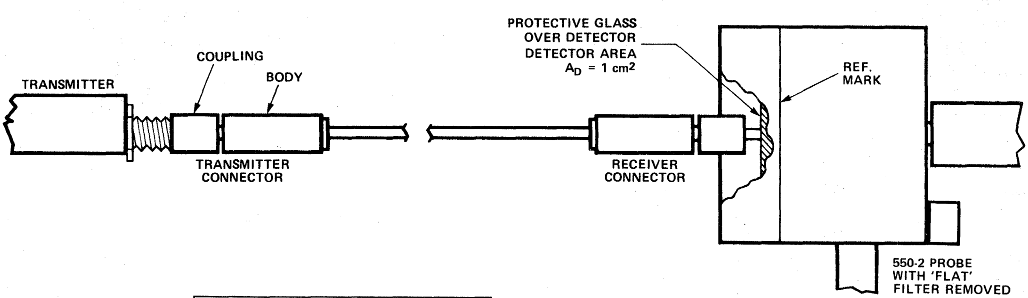
1. OBSERVE E_1 (μW/cm2) WITH 'FLAT' FILTER IN PLACE
2. OBSERVE E_2 (μW/cm2) WITH 'FLAT' FILTER REMOVED

FILTER TRANSMITTANCE: $\boxed{\tau_F = E_1 / E_2}$

AVERAGE FLUX FROM TRANSMITTER: $\boxed{\phi\ (\mu W) = \left[E_1 \left(\frac{\mu W}{cm^2}\right)\right] \left[d^2 (cm^2)\right] \left[\left(\frac{\phi}{I}\right)_{MAX}\right]}$

$\left(\frac{\phi}{I}\right)_{MAX}$ IS THE MAXIMUM VALUE OF THE RADIATION PATTERN INTEGRAL: $\frac{\phi(\theta)}{I(0)}$ (SEE DATA SHEET)

(a) MEASUREMENT OF TRANSMITTER AVERAGE FLUX



GENERAL PROCEDURE SAME AS ABOVE

3. WITH TRANSMITTER CONNECTOR SEATED, CENTER RECEIVER CONNECTOR OVER DETECTOR, THEN POSITION AGAINST GLASS. (DO NOT SLIDE – SLIDING MAY CAUSE SCRATCH DAMAGE.) OBSERVE E_O (μW/cm2).
4. WITHOUT ROTATING THE BODY, ROTATE THE COUPLING BY SMALL INCREMENTS OF TURNS, NOTING THE NUMBER OF TURNS, N, AND FOR EACH VALUE OF N: OBSERVE E_N (μW/cm2).

RECEIVER INPUT FLUX, AT OPERATING LEVEL $\boxed{\phi_O\ (\mu W) = \frac{[E_O\ (\mu W/cm^2)]\ [A_D\ (cm^2)]}{\tau_F\ \text{(SEE ABOVE)}}}$

FLUX DECOUPLING (SEE FIG. 19) $\boxed{\alpha_N = 10 \log_{10}(E_O / E_N)}$

(b) MEASUREMENT OF AVERAGE RECEIVER INPUT FLUX AND FLUX DECOUPLING AT TRANSMITTER CONNECTOR.

Figure 20. Flux Measurement with EG&G Mod 550 Radiometer.

incidance, E, in W/cm2 on an aperture area, $A_D = 1\ cm^2$ and N.A. = 1. With the filter removed, a fiber optic cable can be placed so close to the aperture that there is no flux loss, and since the radiometer N.A. exceeds the fiber N.A., the radiometer will have a reading in W/cm2 which is numerically equal to the flux in watts. However, a correction must be made for the removal of the filter.

The insertion loss of the filter must be evaluated at the measurement wavelength because it varies with wavelength to compensate for spectral variation in the response of the silicon detector. The arrangement shown in Figure 20 for measurement of radiant intensity is a good one for measuring insertion loss of the filter. Two observations are made — one with and one without the filter. Error due to ambient radiation is avoided by working in subdued ambient and for each observation taking two radiometer readings (source off and source on); the difference in readings is the observation of the radiant incidance, E_e, produced by the radiant intensity, I_e, of the source. The ratio of the two observations gives:

$$(28)\ \text{FILTER INSERTION LOSS, } \alpha_F = 10 \log \frac{E_{e(\text{filter out})}}{E_{e(\text{filter in})}}$$

This same arrangement can be used to measure the average flux of the Transmitter as shown in Figure 20b. From the observation of E_e with the filter IN:

$$(29)\ \text{AVERAGE INTENSITY, } I_e\left(\frac{\mu W}{sr}\right) = E_e\left(\frac{\mu W}{cm^2}\right) \times d^2\ (cm^2)$$

from Equation (29)

$$(30)\ \text{AVERAGE FLUX, } \phi_e(\mu W) = I_e\left(\frac{\mu W}{sr}\right)\left[\frac{\phi(\theta)}{I(0)}\ (\text{MAX})\right]$$

value from radiation pattern integral in Transmitter Data Sheet

SYSTEM MAINTENANCE

Preventive Maintenance

Long-term degradation occurs in any LED and LED degradation affects the Hewlett-Packard Fiber Optic System in two ways: reduced average flux, affecting either externally- or internally-coded mode, and altered flux excursion ratio, affecting only the internally-coded mode. Significant degradation of either the flux or the flux excursion ratio can be detected by regular observation of the flux margin, α_M, and of k.

α_M is evaluated as explained under Operating Margin Measurement from Equation (27). A plot of α_M against the logarithm of the cumulative hours of operation will allow an estimate to be made of the operating time remaining until $\alpha_M = 0$ FOR THE P_e DESIRED.

k must be evaluated by measuring ϕ_H, ϕ_M, and ϕ_L as explained in the Transmitter description. The Test Point voltage can be used in making this measurement — see Equation (15). The upper and lower margins on k for a particular Receiver can be found by operating the Transmitter with Mode Select "high" and a rectangular signal ($f \approx 500kHz$) at Data Input. As the duty factor of the signal is varied, the limits on k are found as those at which the Receiver fails to follow the Data Input signal.

$$(31)\ k = \left(\frac{1}{ft_P}\right) - 1 = \frac{1}{\frac{1}{ft_N} - 1}$$

where ft_P is the positive-pulse duty factor
ft_N is the negative-pulse duty factor

Changes in k do not affect externally-coded mode performance, and if this mode is used, then flux margin, α_M, is the only concern.

Corrective Maintenance

Trouble in the System may range from complete breakdown to excessive BER. The flux used in the Hewlett-Packard System is visible so the cause of complete breakdown can sometimes be localized by simply looking at the output of the Cable and the Transmitter. If there is visible output from the cable, then, when the Cable is connected to the Receiver, there should be an 8mV change in Test Point voltage, V_T, as the Transmitter (Mode Select "low") is turned on and off by switching V_{CC}. If ΔV_T is more than 8mV but the system is not working, then either the Receiver logic is not functioning properly or the flux excursion ratio, k, is either too high or too low. Excursion ratio can be checked as described above, using V_T. If k is satisfactory, the logic malfunction could be due to incorrect supply voltage or output loading.

If the System is functioning but has excessive BER, either the flux and flux excursion ratio are marginal (can be checked as described above) or there is too much interference from noise or other effects. If the Data Input voltage levels are correct, either random noise is high or errors are occurring due to incorrect supply voltage or output loading, or due to noise on the supply line. Random noise effects can be checked by lowering the flux level to a point where P_e is measurably high. If P_e varies with flux level according to $P_e = \text{erfc}(X)$, as in Equation (26), then the problem is excessive random noise. Random noise can also be checked by changing the data rate while the flux level is low enough to make P_e measurable. If P_e is the same at any data rate, the problem is excessive random noise. Excessive random noise is more likely to occur in the Receiver than in the Transmitter; the best way to check is by replacement of the Receiver. Noise on the supply line is difficult to trace. If there is any doubt, the Receiver should be operated from its own supply (e.g., a 5V regulator). Receiver noise should be low enough to make $P_e < 10^{-9}$ at 10 Mbaud with normal flux level ($\Delta V_T > 8$ mV by the method described above indicates normal flux level).