Agilent Technologies
Innovating the HP Way

Low Cost Fiber-Optic Links for Digital Applications up to 155 MBd

Application Bulletin 78

The HFBR-2406/16 High Performance Component

The HFBR-2406 and HFBR-2416 are high-speed, low-cost, linear, light-to-voltage converters with typical bandwidths of 125 MHz. These components can be used to make fiber-optic links for both analog and digital applications. Since the range of possible uses is so varied, this Application Bulletin concentrates on a specific digital application. The application is one of the most prevalent for the HFBR-24X6: the transmission of encoded digital signals, otherwise known as run-length limited* data.

The HFBR-0400 component family's inexpensive, one-piece plastic package allows engineers to construct low-cost high-performance fiber-optic links. All devices in the HFBR-0400 product family, including the HFBR-24X6, are available with optical ports that are compatible with the industry standard SMA and ST** fiber-optic connectors. Components that are compatible with the SMA connector are denoted by a "zero" in the third digit of their part numbers. If the ST connector is to be used, the component part number should contain a "one" in the third digit. For example, the equivalent of the high-performance HFBR-2406 SMA-compatible receiver with the ST connector option is the HFBR-2416.

The addition of the HFBR-24X6 receiver to the low-cost 0400 component family opens new avenues for designers. They can now develop fiber-optic links that meet tough cost and performance objectives. The wide bandwidth of the HFBR-24X6 allows high-speed, fiber-optic links to be built at lower prices than was formerly possible. Engineers can exploit the high performance of the HFBR-24X6 in other ways as well. For instance, the wide bandwidth of the linear light-to-voltage converter can be reduced by a low-pass filter to improve the sensitivity of the fiber-optic receiver in lower-speed applications. The HFBR-24X6 accommodates a larger optical signal than other HFBR-0400 fiber-optic receivers before it begins to overload. This improvement in the overload characteristics of the 24X6 was achieved with no significant reduction in the ultimate sensitivity when compared to the existing HFBR-24X4 receiver. The increased optical input power tolerated by the HFBR-24X6 allows it to function at short fiber lengths with large values of launched optical power. When the receiver can tolerate higher optical power, a longer cable is possible before attenuation reduces the light to the sensitivity limit of the receiver. The increased dynamic range of the HFBR-24X6 will thus permit greater optical link length for any given fiber attenuation.

Applications For 820 nm LED Based Fiber Optic Links

The 820-nm LED technology used in the HFBR-0400 family of components can be used in conjunction with the HFBR-24X6 receiver to construct digital fiber-optic links that transmit data at speeds up to 155 MBd. The length of the fiber cable that can be used with the HFBR-24X6 is restricted by the receiver sensitivity at low data rates. As the data rate is increased a phenomenon known as chromatic dispersion begins to limit the maximum distance. Chromatic dispersion results

* Run length limited means a limit on the number of consecutive symbols in the same state.
** ST is a trademark of AT&T Technologies.

from the interaction of the 60 nm-wide spectrum emitted by the LED and the propagation velocities of light in silica. Since the velocities of light at various wavelengths near 820 nm are different, the optical pulses sent by the LED are dispersed or spread out in time as they travel down the light guide. A chromatic dispersion null exists at a wavelength of 1300 nm in silica glass. If an LED were operated at the chromatic dispersion null the pulses would experience the minimum broadening as they traveled through the fiber. This is due to the nearly equal propagation velocity for all the wavelengths transmitted through the silica light guide by the long-wavelength emitter. Figure 1 illustrates the effect of the LED center wavelength and spectral width on the chromatic dispersion. An 820 nm LED with a 60 nm emission spectrum is shown to produce a larger change in the arrival time of the light pulses than a 1300 nm LED with a 100 nm spectral width. When selecting a fiber the designer should be aware of how the bandwidth-length product, expressed in MHz/km, was determined. The bandwidth of a fiber measured using a narrow spectrum emitter, such as a laser diode, is related to the various possible modes of light propagation that can exist in a fiber. This is referred to as the fiber's modal bandwidth. The modal bandwidth will be greater than the chromatic bandwidth which dominates when an LED is used. To determine the overall optical bandwidth of a fiber, the modal and chromatic bandwidths must be combined as an rms sum as shown in Equation 1. In LED-based systems the wavelength, spectral width and response time of the emitter used as the fiber-optic transmitter will affect the final system bandwidth. Thus, to understand how a fiber will work with an LED, one must know the type of optical source used to measure the manufacturer's stated bandwidth. HP HFBR-AWSyyy 100/140 µm fiber-optic cable has a typical optical bandwidth-length product of 40 MHz/km. This value represents the performance of the HP fiber with an 820 nm LED emitter that has a 60 nm spectral width. The 40 MHz/km typical bandwidth-length product of HP fiber results from the combination of the modal and chromatic bandwidths.

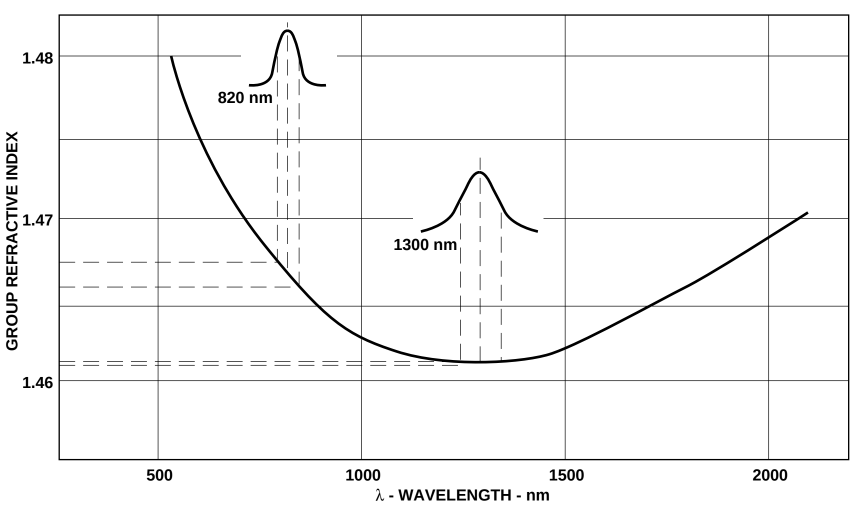


Figure 1. Group Delay vs. Wavelength.

$$\text{B.W.} = \left[\frac{1}{\left(\frac{1}{\text{B.W. modal}}\right)^2 + \left(\frac{1}{\text{B.W. chromatic}}\right)^2}\right]^{1/2}$$

Equation 1.

The typical distances and data rates possible with 820 nm LED emitters and the HFBR-2406/2416 receiver are shown in Figure 2. Note that the data rate versus distance for 100/140 and 62.5/125 µm graded-index fibers are both shown in the figure.[1, 2, 3, 4]

If greater distances or higher speeds are required, other options such as 1300 nm LEDs or laser diodes can meet these objectives. If the system requirements fall to the left of the curves shown in Figure 2 the design goals can be achieved using an 820 nm LED and the HFBR-24X6 for a substantially lower cost than possible with these other technologies. The inexpensive 820 nm LED technology offers the designer a cost-effective solution sufficient for many short-distance applications at data rates in excess of 100 megabaud.

Applications for 820 nm LED Based Systems Using HFBR-2406/2416 Include:

- CPU to disc interface.
- CPU to monitor interface
- CPU to peripheral interface
- Optical data bus applications.

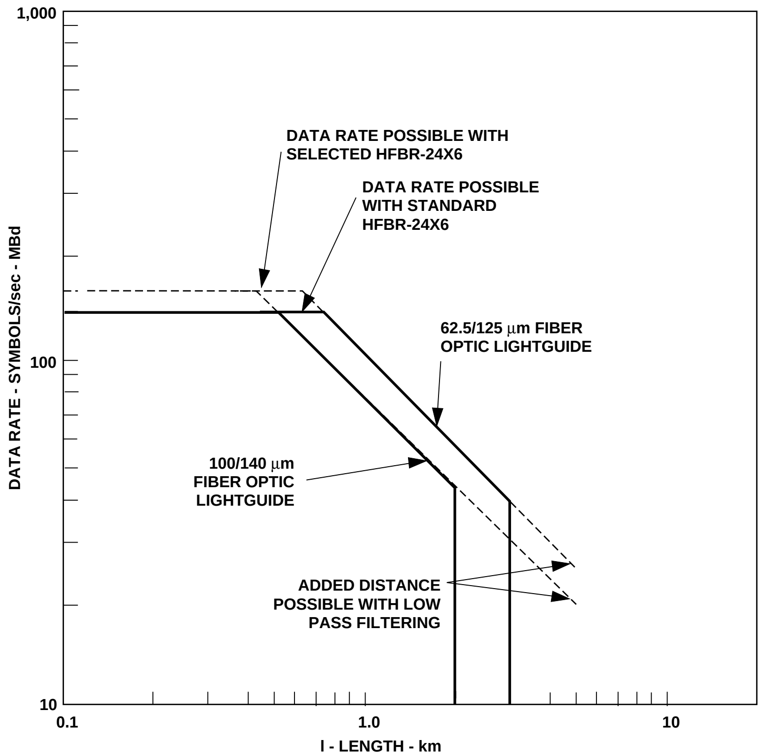


Figure 2. Typical Data Rate and Distance Possible with HFBR-2406/2416.

- Graphics workstation to host computer interface.
- Wide dynamic range, long distance, medium speed LAN applications.
- High-speed, point-to-point data links.
- Security, voltage isolation.

Advantages of Run Limited Code

Data is coded to prevent the digital information from remaining in one of the two possible logic states for an indefinite period of time. The coded data allows the fiber-optic receiver to be ac coupled. Without encoding, the fiber-optic receiver would have to detect dc levels to determine the proper logic state during long periods of inactivity, as when there is no change in the transmitted data. AC-coupled fiber-optic receivers tend to be lower in cost, are much easier to design, and contain fewer components than their dc-coupled counterparts.

Direct coupling decreases the sensitivity of a fiber-optic receiver since it allows the low-frequency flicker noise from the transistor amplifiers to be presented to the comparator input. Any undesired signals coupled to the comparator will reduce the signal-to-noise ratio at this critical point in the circuit, and reduce sensitivity of the fiber-optic receiver.

Another problem associated with direct-coupled receivers is minimizing the accumulation of dc offset. With direct coupling, the gain stages multiply the effects of undesirable amplifier offsets and voltage drifts due to temperature changes, and apply them to the comparator. Increases in the dc offset applied to the comparator result in reduced sensitivity of the fiber-optic receiver. The dc offset at the comparator can be referred to the optical input of the receiver by dividing by the receiver gain. This division refers the dc offset at the comparator to the receiver input where it appears as a change in optical power that must be exceeded before the receiver will switch states.

Another advantage of run-limited coding is related to timing recovery. If NRZ data were transmitted over a serial fiber-optic link the data could be in the logic “1” or logic “0” state for an indefinite period of time. When NRZ data remains in a particular state no transitions occur and the fundamental frequency of the data is dc. This lack of power at the fundamental frequency of the data eliminates the reference signal needed by the timing recovery circuits required to clock the received information. If an optical link is to transmit NRZ data, a clock signal must be sent on a separate fiber-optic link to synchronously detect the incoming serial data.

The particular run-length-limited code chosen must be considered carefully since it will affect the bandwidth required by the serial communication channel. A complete discussion of all run-limited codes is beyond the scope of this publication. If you desire additional information regarding various coding schemes, there are numerous technical papers devoted to this specific topic.[5] Without becoming too involved in the complexity of encoding selection, a quick comparison will now be made between two commonly recognized approaches to this problem.

One of the most familiar run-limited codes is Manchester. Manchester is very popular since it can be encoded and decoded with relatively simple circuits. Manchester works well in ac-coupled systems since it has a 50% duty factor and two pulses or symbols for each bit transmitted. This simplifies the design and implementation of the timing recovery function since Manchester code has only two consecutive symbols without a transition, or a run limit of two. A drawback of Manchester is that two symbols must be sent for each data bit encoded, thus doubling the fundamental frequency that must pass through the information channel. Substitution codes have recently been made available in very large scale integrated (VLSI) circuits. These VLSI circuits function as a general purpose interface between the parallel architecture found in computer-based systems and the serial format required by fiber-optic communication links. The two different substitution codes available in the AMD TAXIchip™ parallel-to-serial encoder are 4B5B and 5B6B. These two codes have an efficiency of 4/5 and 5/6 respectively which compares to an efficiency of 1/2 for Manchester code. The significance of coding efficiency can be illustrated by an example. If an application calls for the transmission of 100 M bits/second, Manchester code requires that the information channel must pass 200 M symbols/second or 200 MBd. If the more efficient 4B5B code were used, 100 M bits/second could be sent at a speed of (5/4)(100 M bit/sec) = 125 MBd. Similarly, use of 5B6B would allow transmission of this data at a speed of (6/5)(100 M bit/sec) = 120 MBd.

Regardless of the particular coding scheme used there will always be two symbols per cycle. This is true because each half cycle of the maximum fundamental frequency that the communications channel must pass is equivalent to a symbol in a binary transmission system.

Designing With Fiber Optic Components

Transmitter Design

Now that the basic issues related to fiber-optic link design have been covered, some specifics related to the design of the optical transmitters and receivers will be discussed in greater detail. To achieve the wide bandwidth performance potential of the fiber-optic medium requires a fast LED and current modulator. The transmitter's pulse-width distortion and optical rise and fall times can be heavily influenced by the driver selected. Readily available off-the-shelf integrated circuit current drivers can be configured with the HFBR-14XX 820 nm LEDs to build high-performance fiber-optic transmitters with a typical pulse-width distortion of 800 psec.

To obtain the best performance from any LED and driver combination, two simple techniques known as prebias and drive current peaking should be employed. Prebias, as its name implies, is a small forward current applied to the LED in the "off" or "low" light state. The prebias current prevents the junction and parasitic capacitances from discharging completely when the LED is in the "off" state, thus reducing the amount of charge that the driver must transfer to turn the emitter back on. Peaking is a momentary increase in LED forward current that is provided by the driver during the rising and falling edges of the current pulses that are used to modulate the emitter. If the time constant of the peaking circuit is approximately equal to the minority carrier lifetime of the emitter, the momentary increase in LED current will transfer charge at a rate that improves the rise or fall time of the light output without causing excessive overshoot of the optical pulses. Problems that can result when excessive peaking is applied to the LED are illustrated in Figure 3. The narrow optical overshoot due to excessive peaking of the transmitter causes a narrow electrical output pulse from the fiber-optic receiver that must now be damped. Even if the receiver amplifiers were critically damped the electrical undershoot resulting from excessive peaking of the emitter can reduce the sensitivity of the fiber-optic link. This electrical undershoot can combine with noise from the amplifiers so that the sum of these two voltages exceeds the decision threshold of the comparator, which converts the low-level analog output of the fiber-optic receiver back to logic-compatible digital signals. Excessive peaking during the turn-off of the emitter can cause additional problems. Too much reverse current during the turn-off transition will reverse-bias the LED, seriously degrading the turn-on time.

A circuit with a low source impedance should be used to drive the LED. This is important because the light output of an LED is proportional to the number of electron hole pairs present in the LED's junction. If high speed operation of the transmitter is desired, a driver with a low source impedance should be used to provide the sudden changes in current required to quickly create and annihilate charge carriers in the LED junction. LEDs are characteristically harder to turn off than to turn on. This difficulty manifests itself as a phenomenon commonly referred to as the long-tailed response. An example of long-tailed response is shown in Figure 4. The long-tailed response is most evident when a simple series switch is used to control the LED drive current as shown in Figure 5. A shunt drive configuration, which turns the LED off when the driver transistor saturates, significantly improves the performance of the LED transmitter. Shunt drive reduces pulse-width distortion and the magnitude of the slow tail by providing a low impedance path for charge stored in the LED junction. Without this low-impedance path the emitter would turn off slowly since the LED would continue to produce light until the diode junction discharges.

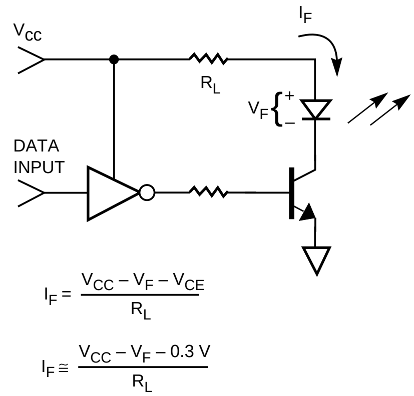


Figure 5. Series Switch LED Driver.

Readily available 74ACT logic gates can be used to implement a shunt drive configuration to current-modulate the LED. A current of 60 mA is typically required to drive the HFBR-14X2/4. Ordinary bipolar TTL gates generally do not have sufficient capability to sink and source 60 mA. A simple high-speed LED driver can be constructed by connecting the active output of 74ACT logic to the HFBR-14X2/4 as shown in Figure 6. In this configuration the pull-up transistor turns the LED off, and the pull-down transistor turns the LED on. The low impedance and high current rating of the MOSFET transistors used in 74ACT output stages allows these gates to quickly inject and remove charge from the LED. The ability of 74ACT gates to quickly move charge is very important as the LED turns off. The dynamic impedance of the LED increases rapidly as forward current decreases at turn off. The LED will continue to emit light as long as the junction contains minority charge carriers. The pull-up transistor of the 74ACT LED driver provides the low impedance discharge path needed to sweep charge from the junction and rapidly quench the light emitted by the LED. The low impedance of the pull-down

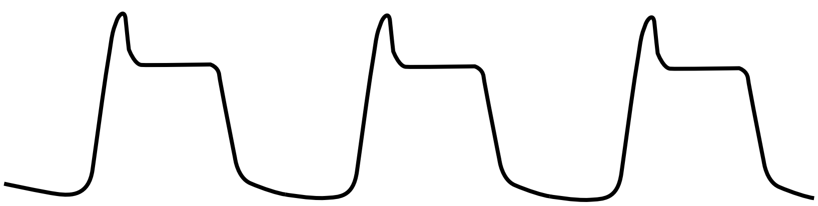


Figure 3a. Optical Overshoot Due to Excessive Peaking of the LED Drive Current.

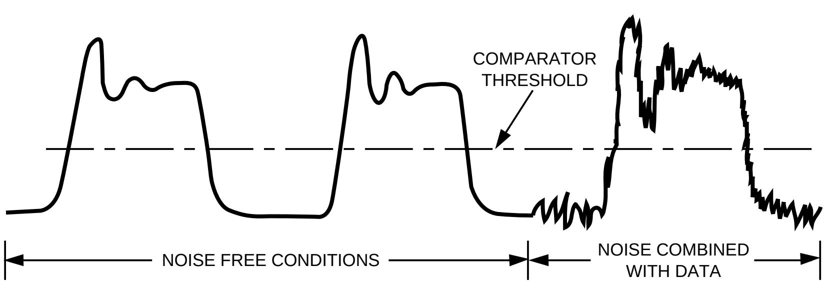


Figure 3b. Response of Optical Receiver to an Excessively Peaked LED Transmitter.

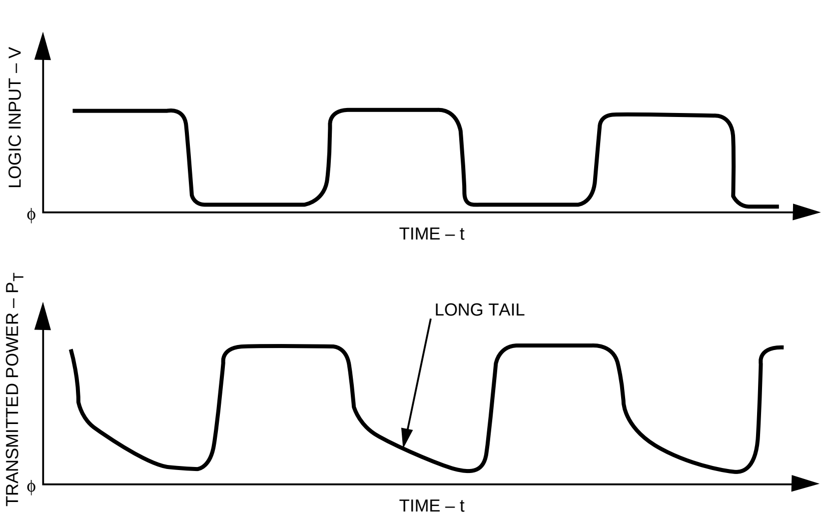


Figure 4. Example of Long-Tailed Response.

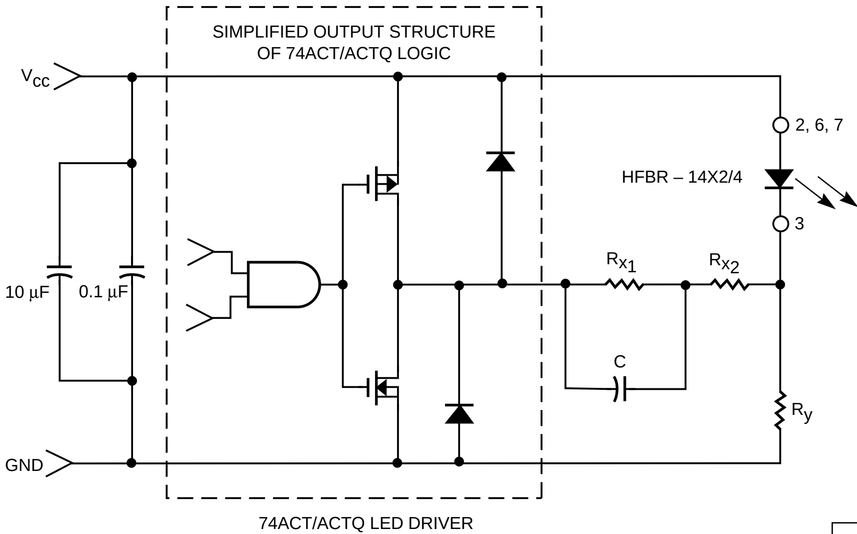


Figure 6. Simple High-Speed Transmitter Circuit.

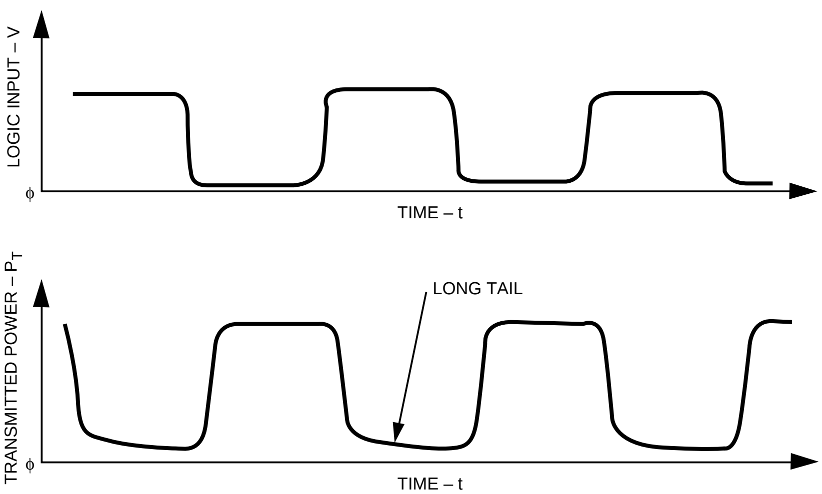


Figure 7. Improved Optical Output Waveform.

Equation 2.

N = The number of 74ACT gates connected in parallel.

B = Is an empirically determined constant which establishes a optimum relationship betwe prebias and LED forward cu

$$R_y = \frac{(V_{cc} - V_F)\,(1 + B)}{I_{F\ ON}}$$

$$R_{x_1} = \left(\frac{R_y}{2B}\right)$$

$$R_{x_2} = \left(\frac{R_y}{2B}\right) - \left(\frac{3}{N}\right)$$

$$C = \frac{2.5\ \text{ns}}{R_{x_1}}$$

transistor ensures that the LED turns on quickly by providing the current needed to rapidly charge the junction during the less difficult turn-on transition. When the 74ACT gate and LED are configured as shown by the schematic in Figure 6, the improvement in the optical output waveform is as shown in Figure 7. The high speed capability of 74ACT logic minimizes the difference between high-to-low and low-to-high propagation delays. The variance between t_{PHL} and t_{PLH} of the gate used to drive the LED will affect the pulse-width distortion present in the transmitter's optical waveform. When nand inverters from the same die are connected as shown in Figure 8 the distortion due to gate propagation delay differences is minimized. The transmitter circuit shown in Figure 8 typically has an optical jitter of 800 ps; this excellent transmitter performance can be achieved when an undistorted TTL signal is applied to the 74ACTQ00 quad nand gate used to current modulate the HFBR-14X2/4 LED.

The transmitter shown in Figure 8 is compatible with TTL logic and is suited for data with a maximum fundamental frequency of 78 MHz, which implies a symbol rate of 155 MBd. The design rules for the LED driver shown in Figure 8 are shown in Equation 2. This simple TTL-compatible fiber-optic transmitter has a typical rise/fall time of 3 ns.

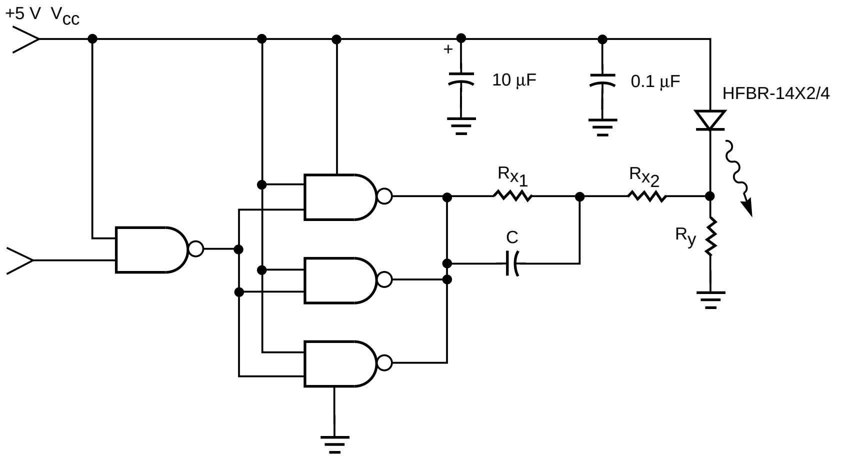


Figure 8. TTL Compatible LED Driver Implemented with 74ACT or 74ACTQ nand Logic.

Testing Fiber Optic Systems

Pseudo-random-bit-sequence (PRBS) generators are very useful for testing the performance of fiber-optic systems. The pseudo-random data pattern contains long periods of inactivity related to the length of the shift register used to build the PRBS generator. A PRBS generator made up of a 23-bit-long shift register could at any given clock time contain one of 8,388,610 possible data patterns. The number of data patterns possible can be calculated as 2^{23}-1 since the state where all shift register stages contain logic zeros is not allowed. These long periods of inactivity in the data pattern produced by the PRBS generator allow time for parasitic capacitances in the transmitter and receiver to charge. The time required to charge and discharge undesired capacitances in the transmitter and receiver result in pulse-width distortion related to the instantaneous duty factor of the data. This phenomenon is known as data dependent jitter or DDJ. If an oscilloscope is clock triggered on the PRBS generator it asynchronously samples the data due to the lack of correlation between the PRBS clock and the time base that generates the horizontal sweep of the scope. When triggered on the PRBS generator's clock the scope will display a signal known as the "eye pattern". The "eye pattern" can be very useful since the width and height of the opening between the data edges defines the time period during which the data is in a valid logic state.

TTL Transmitter Performance

The performance of the circuit shown in Figure 8 was tested using a 2^{23}-1 PRBS data pattern to demonstrate the typical performance of this TTL transmitter. Jitter in the data edges results due to the DDJ induced by the pseudo random bit sequence. The eye pattern shown in Figure 9 reveals that the HFBR-14X2/14X4 LED transmitter had a total data-dependent edge jitter of 800 ps when driven by the 74ACTQ00 gate at a rate of 155 MBd. This data was taken at an ambient temperature of 25°C and represents the typical performance possible with this simple fiber-optic transmitter. The total pulse-width distortion can be further reduced by using a limited-range potentiometer in place of fixed values of R_y for system applications that are extremely intolerant of symbol-width variations. But for most data communications applications, this transmitter performs adequately at speeds up to 155 MBd using fixed component values.

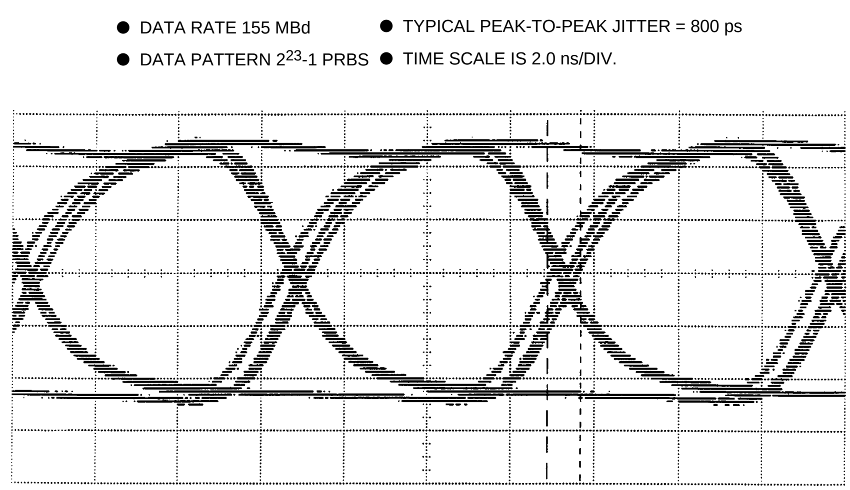


Figure 9. Optical Output of the TTL Transmitter.

ECL Transmitter Performance

If an ECL-compatible fiber-optic transmitter is needed it can be easily built using the circuit shown in Figure 10. The design rules for this high-performance fiber-optic transmitter are given in Equation 3. This particular transmitter uses a simple ECL to TTL converter and 74ACTQ nand logic in conjunction with the HFBR-14X2/X4 LED emitter. It is capable of typical optical rise/fall times of 3 nsec. The performance of the ECL transmitter was measured with a BCP Model 300 Optical Waveform Receiver. Figure 11 shows the optical "eye" pattern when a 155 MBd pseudo-random-bit-sequence of 2^{23}-1 is applied to the ECL transmitter.

Equation 3. Design Rules for 74ACTQ00 LED Driver Circuits.

N = Number of gates connected in parallel.

B = Empirically determined constant for optimum relationship bet prebias and LED forward c

$$R10 = \frac{(V_{cc} - V_F)(1 + B)}{I_{F\ ON}}$$

$$R8 = \frac{R10}{2B}$$

$$R9 = \frac{R10}{2B} - \frac{3}{N}$$

$$C4 = \frac{2.5 \times 10^{-9}}{R8}$$

Recommend B = 3.97

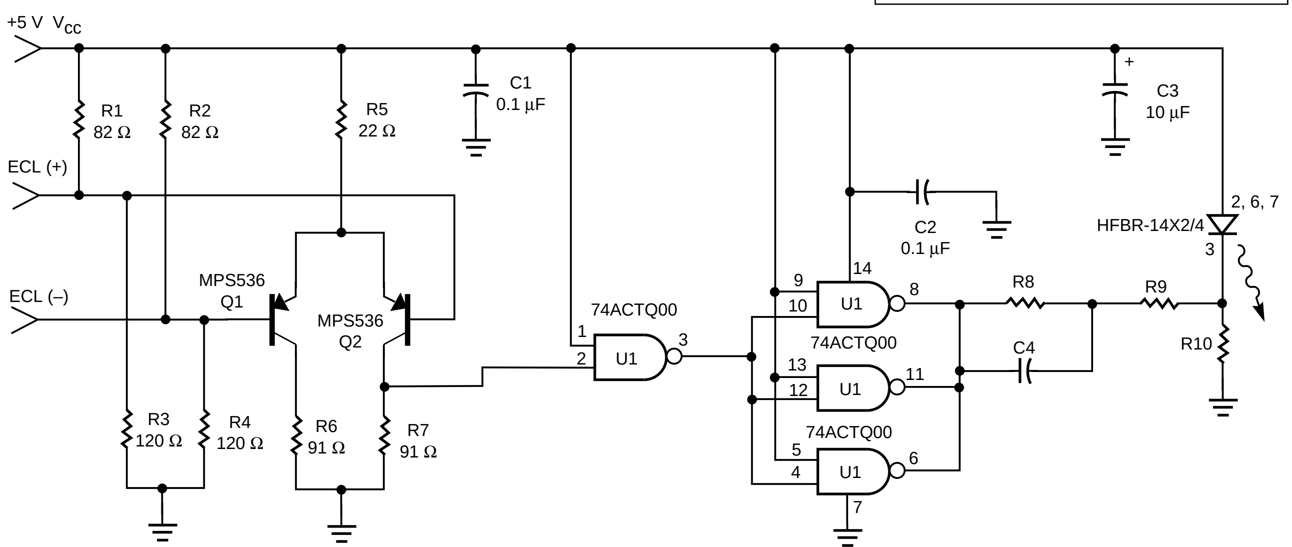


Figure 10. Transmitter with +5 V ECL Interface.

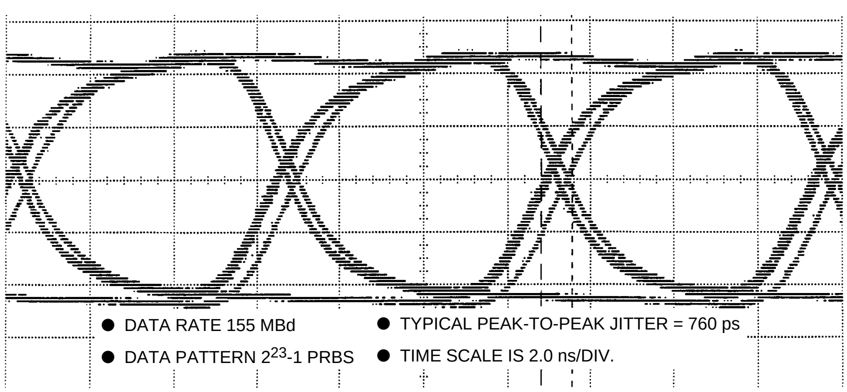


Figure 11. Optical Output of the +5 V ECL Transmitter.

Receiver Design

Now that the techniques required to build high-speed fiber-optic transmitters have been explained, emphasis must be placed on the methods necessary for design and construction of the fiber-optic receiver. Figure 12 shows the functional blocks required to interface the HFBR-24X6 light-to-voltage converter to digital logic. The HFBR-24X6 has a low-level analog output related to the incoming optical power by the 7 mV/µW conversion gain of the light-to-voltage transducer. The HFBR-24X6 needs additional external gain stages to increase the amplitude of its output before it can interface to any of the standard logics like TTL or ECL. The output voltage of the HFBR-24X6 is proportional to the received optical flux. Since the received optical power changes as a function of the fixed optical losses and as a function of fiber-optic link length, some provision must be made to accommodate the change in the output voltage of the light-to-voltage transducer. An amplifier with AGC or a limiting amplifier is needed to accommodate the wide range of output voltages that are possible under various fiber link operating conditions. In the following example, calculations show that the output voltage of the HFBR-24X6 could range from a minimum of 2.9 mV pp to a maximum of 1.74 V pp. This output voltage range is for worst-case conditions at a BER less than or equal to 1×10^{-9} when the component operates between -40 to +85°C.

Calculation of HFBR-24X6 Output Voltage Range

The peak-to-peak signal to rms noise ratio needed at the comparator input for a BER of 1×10^{-9} = 12:1.

This implies an extinction-to-peak (peak-to-peak) change in the received optical flux of (12) (rms noise) will be required. Thus, the peak-to-peak-to-rms-noise ratio required by the fiber-optic receiver for a BER of 1×10^{-9} becomes $(\text{Signal}_{pp}) / (\text{noise}_{rms}) = 12:1$.

The noise floor of the HFBR-24X6 is -43 dBm rms typical.

-43.0 dBm + [10 log (12/1)] = -43.0 dBm + 10.8 dB = -32.2 dBm pk. Thus -32.2 dBm pk is the minimum received optical power that will yield a BER better than or equal to 1×10^{-9}.

-32.2 dBm implies [antilog (-32.2/10)](1,000) = 0.603 µW minimum received optical power for BER better than or equal to 1×10^{-9}.

This minimum power of 0.603 µW implies a change in the receiver input from approximately 0 µW to 0.603 µW or a peak-to-peak change of approximately 0.603 µW pp. The minimum output of the HFBR-24X6 thus becomes (0.603 µW pp)(4.5 mV/µW) = 2.71 mV pp.

The HFBR-24X6 overloads at -8.2 dBm worst-case minimum. Overload is specified as P_r maximum on the data sheet. Overload is defined as the received optical power at which the output pulses from the HFBR-24X6 are distorted 2.5 ns due to saturation of the transimpedance amplifier that converts photo-current to voltage.

-8.2 dBm implies [antilog (-8.2/10)](1,000) = 151 µW. Thus the maximum allowed power of 151 µW implies a change in the receiver input from approximately 0 µW to 151 µW or a peak-to-peak change of approximately 151 µW pp. Thus a maximum received optical power of 151 µW implies a maximum output voltage of (151 µW pp) (11.5 mV/µW) = 1.74 V pp.

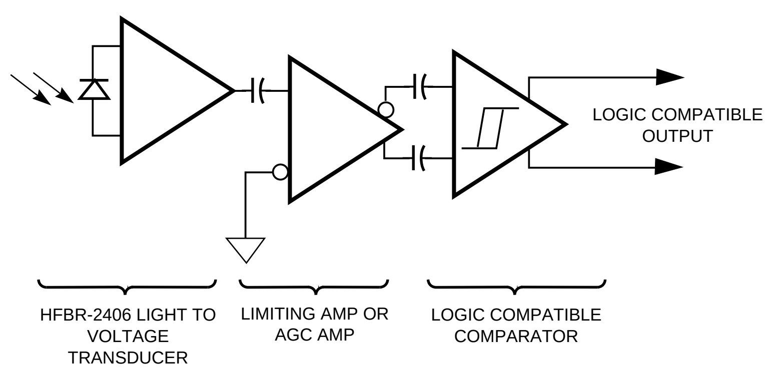


Figure 12. Fiber-Optic Receiver Block Diagram.

Error Rate Versus Signal-to-noise Ratio

The bit error rate (BER) possible with a fiber-optic link is a function of the difference between the peak-to-peak signal and the RMS noise voltages present at the comparator input. A linear relationship exists between optical power entering the HFBR-24X6 and the voltage output of the fiber-optic receiver, provided that interstage coupling and post amplifiers do not introduce significant distortion. This linear relationship implies that if a peak-to-peak signal voltage 12 times larger than the RMS noise voltage is needed at the comparator to ensure a BER of 1 x 10^{-9}, then the same ratio will be required at the receiver input. Thus the difference between the peak-to-peak optical input of light pulses applied to the HFBR-24X6 and the RMS equivalent noise power referred to the optical input must also be 12 to 1. Some confusion exists because changes in the emitter output from extinction to maximum power are often referred to as peak excursions of the transmitter launched power. This confusion results since the transmitter output is varying from zero light to a maximum or peak light output. The extinction-to-on excursion in the optical output of an emitter is actually a peak-to-peak change in intensity. Figure 13 is a graph of receiver signal-to-noise ratio versus BER. The relationship shown in Figure 13 was obtained from extensive reduction of statistical theory that relates the probability of an error to the receiver's signal-to-noise ratio.

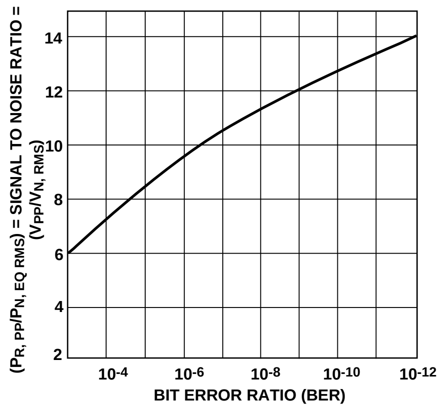


Figure 13. Signal-to-Noise Ratio vs. Probability of Error.

Advantages of Hysteresis

The use of hysteresis in the digitizer will not change the signal-to-noise ratio required at the comparator for a particular BER. Hysteresis will, however, introduce a discontinuous response in the receiver that alters the ratio between peak signal level and the RMS noise in stages prior to the comparator. When dual-threshold detection is used, the signal-to-noise ratio required at the decision circuit for a particular error rate is unaffected but the change in the received power level required to switch the state of the comparator is increased in proportion to the amount of the hysteresis. Dual-threshold receivers experience a reduction in sensitivity proportional to the amount of hysteresis used; however, this type of digitizer offers some interesting advantages. Hysteresis is used in all the receivers shown in this Application Bulletin. Use of hysteresis insures that the logic output of the fiber-optic receiver will not toggle in response to the rms output noise voltage of the HFBR-24X6 when no fiber is connected.

Low-pass Filtering to Enhance Receiver Sensitivity

The importance of filtering to eliminate unnecessary receiver bandwidth becomes apparent by studying Figure 14, which shows the relationship between frequency and the spectral noise density of the HFBR-2406/2416. If the fiber-optic link under consideration were intended for operation at 50 MBd (which implies a fundamental data frequency of 25 MHz) a substantial increase in receiver sensitivity can be realized. This increase in sensitivity is obtained by filtering out the noise peak that occurs in the HFBR-24X6 at higher frequencies than required for this application.

The selection of the low-pass filter corner frequency should be carefully considered since it is affected by the response of the transmitter, fiber, and receiver. To prevent problems that will cause interference between adjacent pulses of data transmitted over the fiber-optic communications channel, the bandwidth of the entire system from transmitter to receiver must be properly specified. A problem known as intersymbol

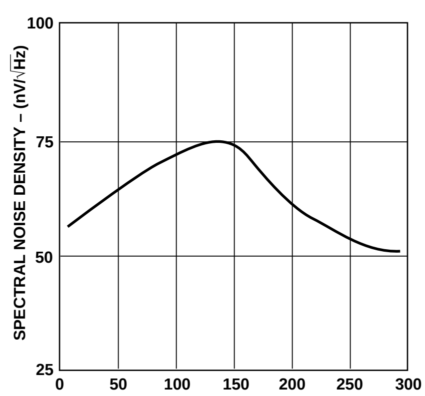
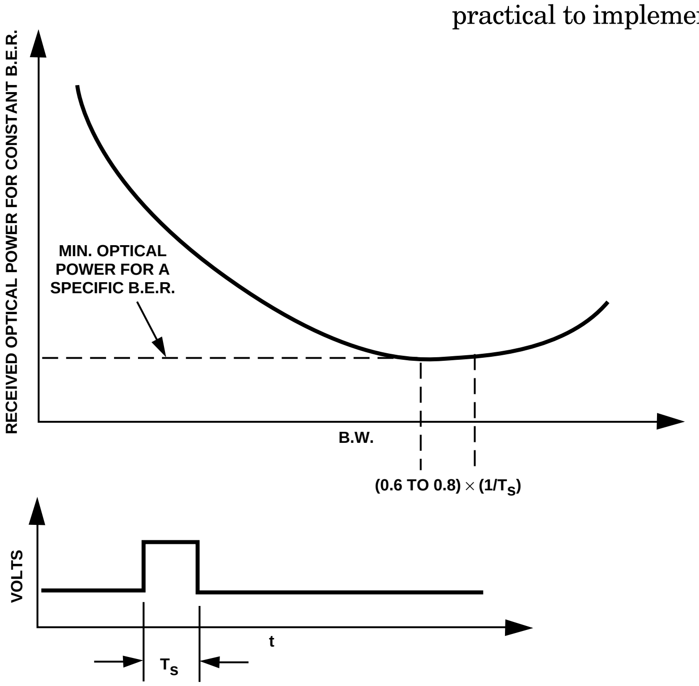


Figure 14. Frequency vs. Spectral Noise Density of the HFBR-2406/2416.

interference develops when the channel bandwidth is not correctly related to the minimum pulse width of the data that is to be transmitted over the communications system. Insufficient system bandwidth manifests itself as distortion in the receiver output signal at time intervals adjacent to the edges of each symbol. This distortion results in interference between adjacent pulses, which can combine with system noise to create errors. Noise is also directly related to bandwidth. Thus, fiber link performance and BER will degrade if system components are excessively fast. For optimum performance that minimizes the amount of optical power required at the receiver for a given BER, the system bandwidth should ideally be constrained to range between 0.6 to 0.8 times the signaling rate in baud, as shown in Figure 15a. If the bandwidth of the fiber-optic communications channel is excessive, a low-pass filter that restricts the system bandwidth to the amount shown in Figure 15a should be constructed in the fiber-optic receiver, at a point ahead of the decision circuit or comparator. For best results the low-pass filter chosen to limit the bandwidth should be a high-order, linear-phase type whenever practical. As the frequency increases, the cost and complexity of a linear-phase high-order filter may become excessive. These higher-speed applications will continue to benefit from a simple first-order or second-order RC low-pass filter that will still be practical to implement.



T_S IS THE MINIMUM PULSE WIDTH OF THE INFORMATION SENT OVER THE COMMUNICATION CHANNEL.

$B.W._{OPTIMUM}$ = [0.6 TO 0.8] (Hz/ baud) × [1/T_S] (SYMBOLS/sec)

$B.W._{OPTIMUM}$ = [0.6 TO 0.8] (Hz/ baud) × [1/T_S] (baud)

Figure 15a. Optimal Relationship Between Fiber-Optic Link Bandwidth and Maximum Receiver Sensitivity.

Compromises Associated With High Speed 820 nm Links

Systems with bandwidths less than (0.6 to 0.8) x (baud) will continue to function since catastrophic failure does not result if these recommendations are violated. Fiber-optic links with bandwidths less than (0.6 to 0.8) x (baud) will have a smaller optical power budget (OPB) than comparable optical links which operate in the flat portion of Figure 15b. This reduction in the OPB is sometimes called the chromatic dispersion power penalty. A decrease in the OPB due to chromatic dispersion is most apparent as an increase in the received power needed to assure a specific BER. The chromatic dispersion power penalty can be directly measured by testing the same transmitter and receiver with both long and short fibers. A fiber-optic link operated beyond the flat portion of Figure 15b requires more received optical power to offset the reduction in signal amplitude due to chromatic bandwidth limitations. Chromatic bandwidth limitations can be overcome if sufficient power is available at the receiver to provide the signal-to-noise ratio necessary for the BER required. The -32 dBm average sensitivity typically obtained when HFBR-24X6 is operated

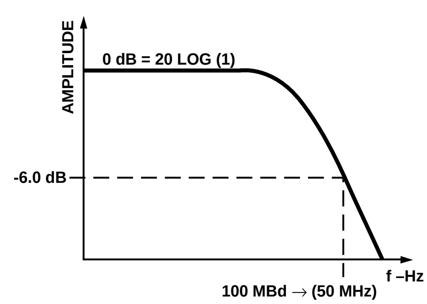


Figure 15b. Optical Link with Normalized Mid-Band Amplitude Response.

with short fibers will allow longer fiber-optic links to operate at frequencies beyond the flat portion of the system's amplitude response. Figure 15b is an example of an optical link whose mid-band amplitude response has been normalized to one. If this hypothetical link were operated at a frequency that reduced the total system output to 6 dB below mid-band amplitude, excess optical power margin (OPM) can still be shown to exist. This excess OPM, as calculated in Equation 4, is sufficient for low-error transmission of 100 MBd data over a 1 km length of 62.5/125 graded index fiber. The HFBR-24X6 receiver has typically demonstrated a BER less than or equal to 1 x 10^{-9} at received optical powers of -32 dBm average (-29 dBm peak) at 100 MBd with a short 1 m length of fiber. In this somewhat pessimistic example, the link sensitivity was assumed to decrease by 6 dB, due to chromatic dispersion of a 1 km length of 62.5/125 µm fiber. The following calculation shows that an ample 3.25 dB OPM remains to assure that the BER is better than 1 x 10^{-9} when 100 MBd data is transmitted over a 1 km length of 62.5/125 µm fiber.

High-frequency Circuit Design

The HFBR-24X6 and each of the amplifiers used in the 10H116 are stable gain blocks that have no tendency to oscillate. Although each of these components is individually stable, the combined phase shift and gain that results when they are cascaded might produce oscillation unless proper circuit construction techniques are used. The effect of all the amplifier poles that accumulate as the signal is amplified and digitized by the various gain blocks in the receiver results in a very steep high-order roll-off for the overall input-to-output open-loop receiver gain. In essence, the fiber-optic receiver relies on the fact that it is an open-loop system. It has sufficient gain and phase shift to meet the criteria for oscillation if the loop were to be closed. To assure stability the loop gain must be kept to less than unity; to prevent oscillation the attenuation of parasitic and conductive feedback paths must be greater than the gain of the receiver. Parasitic feedback from the high-level logic-compatible output must be kept to a minimum by layouts that physically separate the receiver inputs and outputs. Filtering must be used to ensure that power supply busses do not provide a metallic feedback path that will degrade the stability of the receiver, and a ground plane is recommended to minimize the inductance of supply commons.

When good layout practices are employed, fiber-optic receivers with 155 MBd data rates can be easily constructed using commonly available breadboarding techniques. A sound breadboard technique suitable for prototyping the HFBR-2406/2416 can be implemented using perforated PC boards with holes on tenth-inch centers and a copper-clad ground plane on one side only. Use a small hand-held twist drill holder (pin vise) and a number 32 drill to clear copper away from holes through which the component leads will pass. Do not clear all the copper away between these holes. This copper provides ground connections between each IC lead, thus reducing ground-loop size and increasing circuit performance. Install the components on the copper foil side using the component leads for point-to-point wiring interconnections on the insulated side of the board. Production fiber-optic systems can

Equation 4.

OPM (dB) = Optical power margin.

P_R (dBm) = Optical power required at HFBR-24X6 receiver for BER $\leq$ 1 x 10^{-9}.

P_T (dBm) = Transmitter launched power

CDP (dB) = The chromatic dispersion power penalty due to fiber bandwidth, response time of the transmitter, and response time of the receiver.

α_o (l) (dB) = fiber loss.

$$OPM = -(P_R) + P_T - \alpha_o(l) + CDP$$

$$OPM = -(-29\ dBM) + (-16\ dBm) - (3.75\ dB/km)\ (1\ km) - 6\ dB$$

$$OPM = 3.25\ dB$$

be implemented on ordinary double-sided G-10 printed circuit material or multi-layer boards as long as the layout practices discussed here are observed.

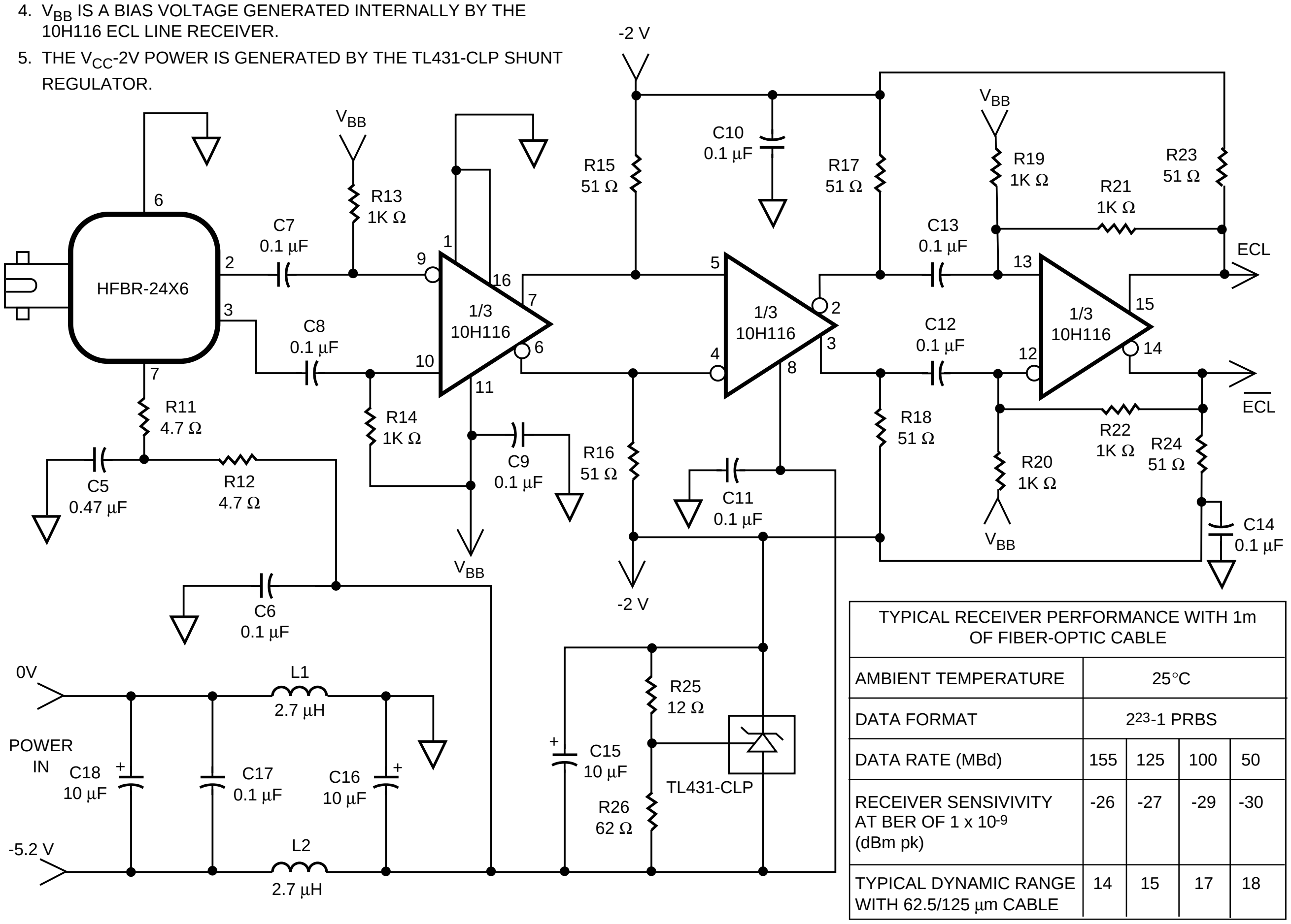
The importance of good construction and layout practices cannot be over-stressed: poor circuit design will seriously degrade system performance. Circuit designs that result in excessive amounts of parasitic inductance or capacitance will degrade the stability and bandwidth of the fiber-optic receiver. Any unintended reduction in the bandwidth or stability of the receiver will result in loss of receiver sensitivity or, in the case where received optical power is held constant, could degrade the BER. It is generally acknowledged that the receiver is the most critical portion of the fiber-optic link electronics. Despite this tendency to focus on the receiver, careful attention must be paid to the transmitter. Care should be taken to keep traces short in the transmitter to minimize inductance of conductors that must carry fast current pulses which can reach momentary peak values as large as 140 mA.

EMI Issues

If a fiber-optic transceiver is to be constructed, additional attention must be paid to minimize crosstalk between a transmitter that is switching hundreds of milliamps and a receiver whose optical detector will have photocurrents as small as hundreds of nanoamps. Individual ground

NOTES:

1. ALL RESISTORS ARE ±5% TOLERANCE.
2. ALL ELECTROLYTIC CAPACITORS ARE ±20% TOLERANCE. ALL OTHER CAPACITORS SHOULD BE RADIAL LEAD MONOLITHIC CERAMIC TYPES WITH ±10% TOLERANCE.
3. L1 AND L2 SHOULD HAVE A ±10% TOLERANCE, SERIES RESISTANCE OF ROUGHLY 0.5 Ω, AND A SELF RESONANT FREQUENCY ≥ 100 MHz.
4. V_{BB} IS A BIAS VOLTAGE GENERATED INTERNALLY BY THE 10H116 ECL LINE RECEIVER.
5. THE V_{CC}-2V POWER IS GENERATED BY THE TL431-CLP SHUNT REGULATOR.



TYPICAL RECEIVER PERFORMANCE WITH 1m OF FIBER-OPTIC CABLE				
AMBIENT TEMPERATURE	25°C			
DATA FORMAT	2^{23}-1 PRBS			
DATA RATE (MBd)	155	125	100	50
RECEIVER SENSIVIVITY AT BER OF 1 x 10^{-9} (dBm pk)	-26	-27	-29	-30
TYPICAL DYNAMIC RANGE WITH 62.5/125 µm CABLE	14	15	17	18

Figure 16a. 155 MBd Fiber-Optic Receiver for -5.2 V ECL Interface.

planes are recommended for the transmitter and the receiver if they are to be laid out next to one another as is typically done in transceivers. The receiver designs shown in Figures 16a, 17a & 18a use a balanced power supply filter that eliminates noise conducted by both the power and common sides of the voltage source used to power the circuit. This filter should be located between the fiber-optic receiver and the noisy voltage source that powers the digital logic to which the fiber-optic receiver must interface. The fiber-optic transmitter can be directly connected to the noisy logic power supply. The transmitter is a large signal device that is not particularly sensitive to digital system noise. Note that when using the balanced power filter a differential interface between the receiver's digital output and the host systems is required.

Another factor that could degrade the performance of a fiber-optic receiver is environmental noise. The HFBR-2406/2416 combines the PIN diode optical detector and the current-to-voltage converter in a small hybrid package. This miniature hybrid package reduces the size of the antenna at the high-impedance input of the transimpedance amplifier that converts the photo-current to a voltage. The small geometry of this hybrid circuit allows the light-to-voltage converter to achieve excellent electro-magnetic interference immunity. Caution must be exercised, however, to ensure that the metal ferrule of the fiber-optic connector does not act as an EMI source by contacting electrically noisy parts of the system in which it is used. Electrostatic shielding should be applied to the receiver if the system using the fiber-optic link is extremely noisy. For noisy system applications the HFBR-2406C or HFBR-2416TC receivers should be specified. The HFBR-2406C and HFBR-2416TC utilize a conductive plastic housing which provides the shielding needed for electrically noisy environments. The conductive plastic receivers can be used in systems that have EMI fields as large as 10 volts/meter (see AN-1057). Another method that improves the EMI

TYPICAL PEAK POWER COUPLED INTO A 1m LENGTH OF FIBER-OPTIC CABLE
I_F = 60 mA T_A = 25°C

FIBER CABLE	NA	HFBR-14X2	HFBR-14X4
100/140 µm	0.3	-12.0	-6.5
62.5/125 µm	0.275	-16.0	-12.0
50/125 µm	0.20	-18.8	-15.8

NOTES:
1. ALL RESISTORS ARE ±5% TOLERANCE.
2. ALL ELECTROLYTIC CAPACITORS ARE ±20% TOLERANCE. ALL OTHER CAPACITORS SHOULD BE RADIAL LEAD MONOLITHIC CERAMIC TYPES WITH ±10% TOLERANCE.

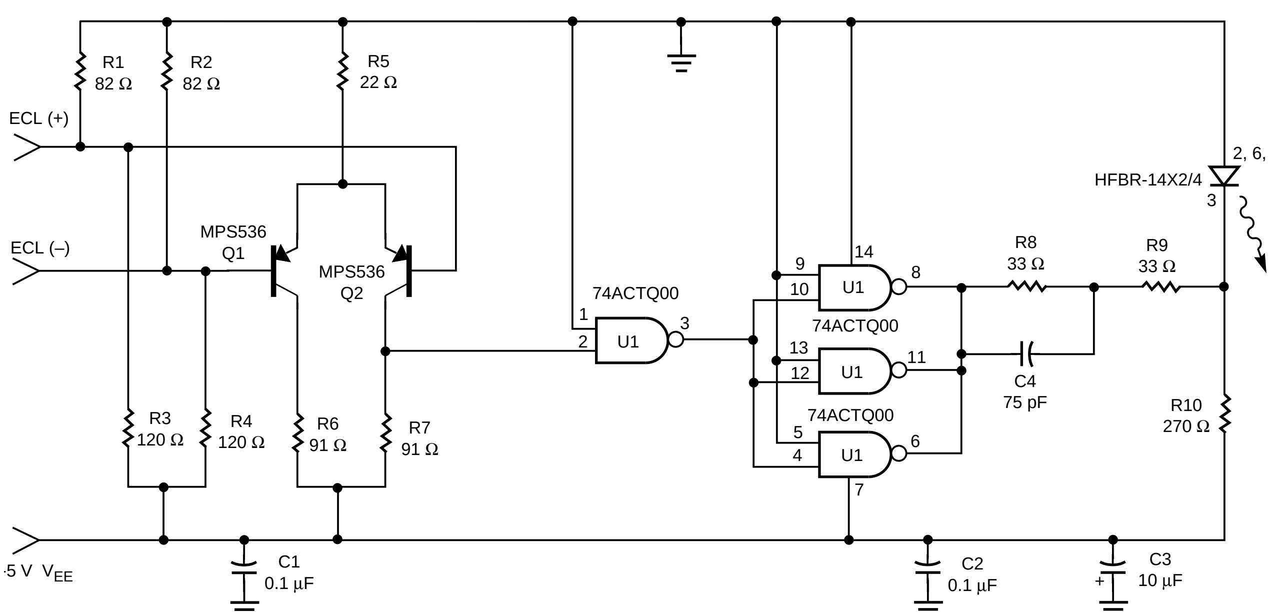


Figure 16b. 155 MBd Fiber-Optic Transmitter for -5.2 V ECL Interface.

TYPICAL RECEIVER PERFORMANCE WITH 1m OF FIBER-OPTIC CABLE				
AMBIENT TEMPERATURE	25°C			
DATA FORMAT	2^{23}-1 PRBS			
DATA RATE (MBd)	155	125	100	50
RECEIVER SENSIVIVITY AT BER OF 1 x 10^{-9} (dBm pk)	-26	-27	-29	-30
TYPICAL DYNAMIC RANGE WITH 62.5/125 µm CABLE	14	15	17	18

NOTES:

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2. ALL ELECTROLYTIC CAPACITORS ARE ±20% TOLERANCE. ALL OTHER CAPACITORS SHOULD BE RADIAL LEAD MONOLITHIC CERAMIC TYPES WITH ±10% TOLERANCE.
3. L1 AND L2 SHOULD HAVE A ±10% TOLERANCE, SERIES RESISTANCE OF ROUGHLY 0.5 Ω, AND A SELF RESONANT FREQUENCY ≥ 100 MHz.
4. V_{BB} IS A BIAS VOLTAGE GENERATED INTERNALLY BY THE 10H116 ECL LINE RECEIVER.
5. THE V_{CC}-2V POWER IS GENERATED BY THE TL431-CLP SHUNT REGULATOR.

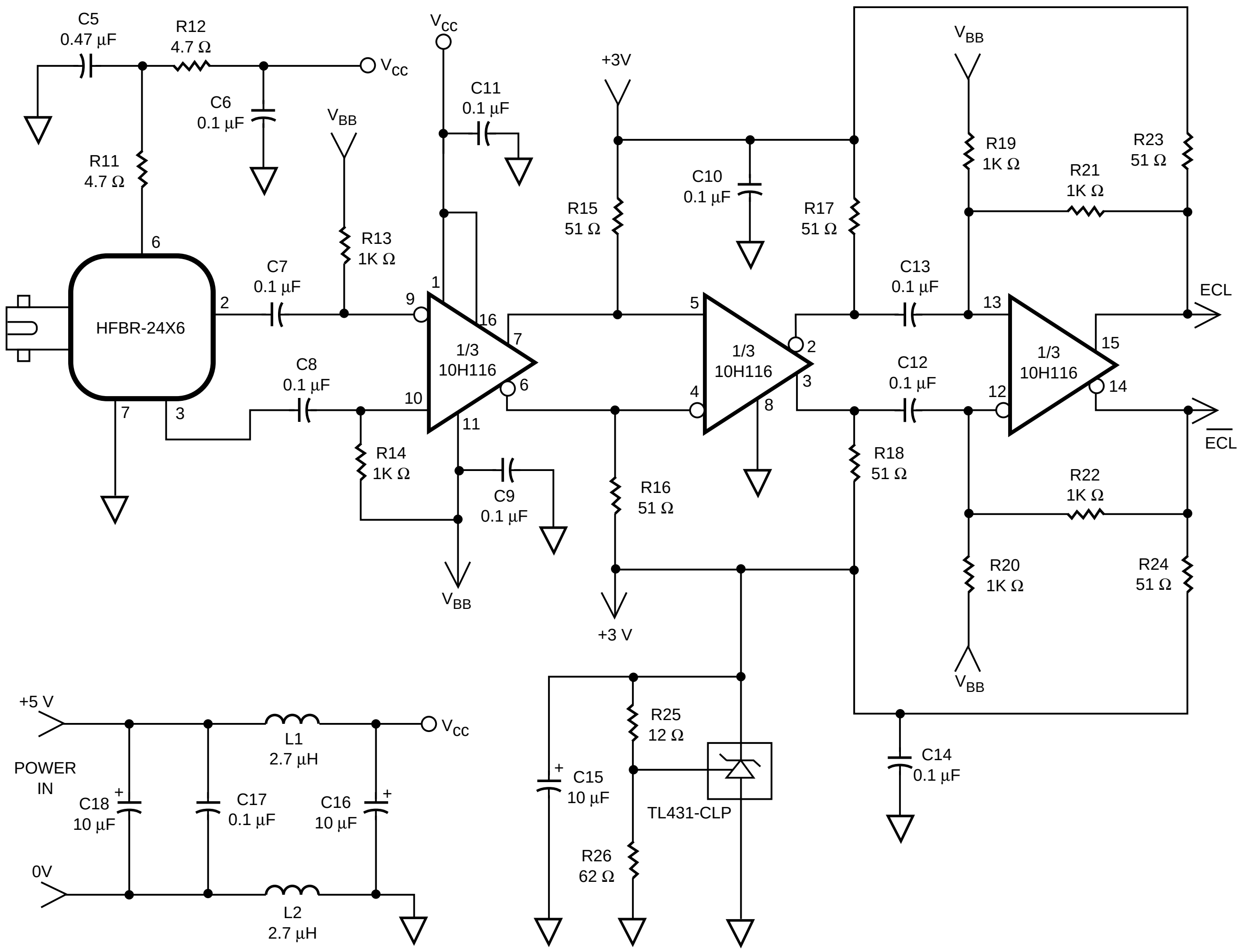

Figure 17a. 155 MBd Fiber-Optic Receiver for +5 V ECL Interface to Am 7969.

immunity of the receiver is to use a connector with a non-conductive plastic or ceramic ferrule. In extremely noisy applications the fiber-optic receiver can be enclosed in a metal box. This box eliminates noise that would otherwise be coupled into the fiber-optic receiver from the system in which it is installed. Systems that require metal shielding have proved to be unusual. Thus, in the majority of applications, the inherent noise immunity of the components combined with the shielding provided by the receiver ground plane have provided sufficient noise immunity.

Applications Support

Some complete designs that allow the use of HFBR-2406/2416 for run-length-limited data applications will now be discussed. Various transceivers have been designed which permit the HFBR-2406/2416 to be interfaced with:

(1) ECL logic operating on -5.2V. (Figure 16)
(2) The AMD TAXIchip™ +5V 100K ECL interface. (Figure 17)
(3) TTL logic operated on +5V. (Figure 18)

At an ambient temperature of 25°C all three interface circuits provided a typical receiver sensitivity of -29 dBm average with a BER of 1 x 10^{-9} at a data rate of 155 MBd. Sensitivity at 125 MBd is typically -30 dBm average at a BER of 1 x 10^{-9}. Figure 19 shows the typical performance of the ECL transmitter/receiver at 25°C. Note that in this test a 2^{23}-1 PRBS pattern at 155 MBd was transmitted over 500 m of 62.5/125 µm graded-index fiber at a BER less than 1 x 10^{-9}. If the low-cost, high-performance fiber-optic links possible with the HFBR-2406/2416 interest you, contact your local HP Field Sales Engineer for additional assistance. Your local HP sales representative can simplify your prototyping task by providing complete artwork for the fiber-optic transmitters and receivers discussed in this Application Bulletin.

*TAXIchip is a registered trademark of Advanced Micro Devices Inc.

TYPICAL PEAK POWER COUPLED INTO A 1m LENGTH OF FIBER-OPTIC CABLE
I_F = 60 mA T_A = 25°C

FIBER CABLE	NA	HFBR-14X2	HFBR-14X4
100/140 µm	0.3	-12.0	-6.5
62.5/125 µm	0.275	-16.0	-12.0
50/125 µm	0.20	-18.8	-15.8

NOTES:
1. ALL RESISTORS ARE ±5% TOLERANCE.
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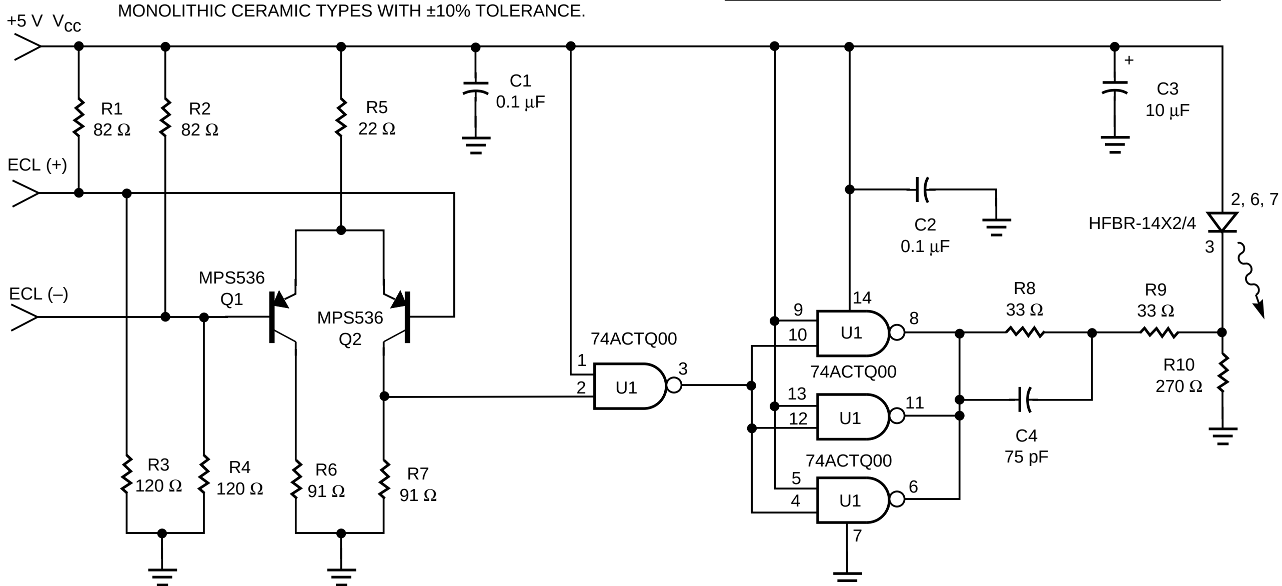
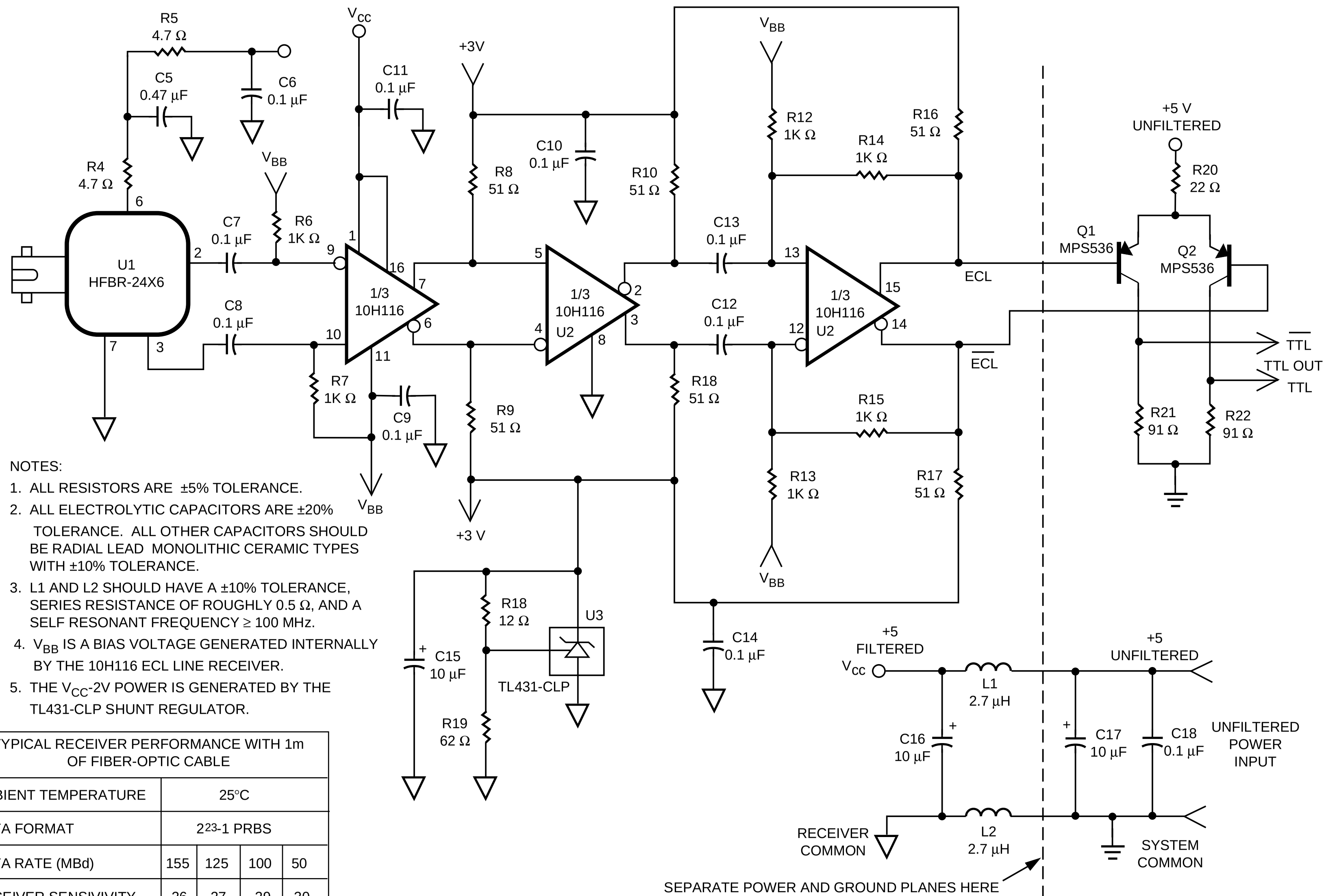


Figure 17b. 155 MBd Transmitter for +5 V ECL Interface to Am 7968.



NOTES:

1. ALL RESISTORS ARE ±5% TOLERANCE.
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3. L1 AND L2 SHOULD HAVE A ±10% TOLERANCE, SERIES RESISTANCE OF ROUGHLY 0.5 Ω, AND A SELF RESONANT FREQUENCY ≥ 100 MHz.
4. V_{BB} IS A BIAS VOLTAGE GENERATED INTERNALLY BY THE 10H116 ECL LINE RECEIVER.
5. THE V_{CC}-2V POWER IS GENERATED BY THE TL431-CLP SHUNT REGULATOR.

TYPICAL RECEIVER PERFORMANCE WITH 1m OF FIBER-OPTIC CABLE				
AMBIENT TEMPERATURE	25°C			
DATA FORMAT	2^{23}-1 PRBS			
DATA RATE (MBd)	155	125	100	50
RECEIVER SENSIVIVITY AT BER OF 1×10^{-9} (dBm pk)	-26	-27	-29	-30
TYPICAL DYNAMIC RANGE WITH 62.5/125 µm CABLE	14	15	17	18

Figure 18a. 155 MBd Fiber-Optic Receiver for TTL Interface.

TYPICAL PEAK POWER COUPLED INTO A 1m LENGTH OF FIBER-OPTIC CABLE I_F = 60 mA T_A = 25°C			
FIBER CABLE	NA	HFBR-14X2	HFBR-14X4
100/140 µm	0.3	-12.0	-6.5
62.5/125 µm	0.275	-16.0	-12.0
50/125 µm	0.20	-18.8	-15.8

NOTES:

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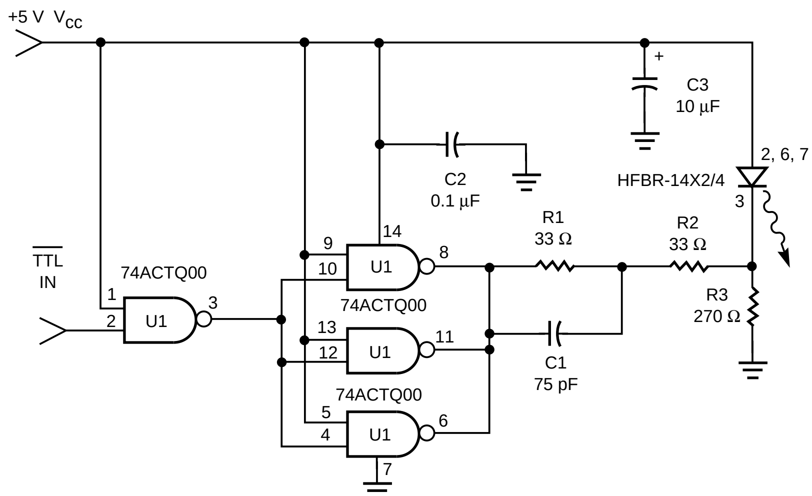

Figure 18b. 155 MBd Fiber-Optic Transmitter for TTL Interface.

- DATA RATE 155 MBd
- DATA PATTERN 2^{23}-1 PRBS
- FIBER TYPE SIECOR 62.5/125 µm
- FIBER LENGTH 500 m
- TYPICAL PEAK-TO-PEAK JITTER = 760 ps
- TIME SCALE IS 2.0 ns/DIV.

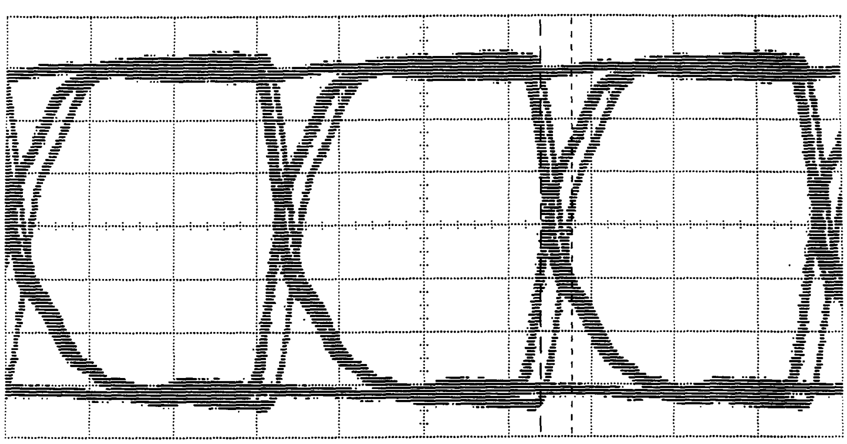

Figure 19. ECL Output of the Transceiver Shown in Figures 17a and 17b.

Complete Transceiver Solution

Figure 21 shows the schematic for a complete fiber-optic transceiver. This transceiver is constructed on a printed circuit, which is 1" wide by 1.78" long, using surface mount components. The transceiver in Figure 21 has an industry standard +5 V ECL (PECL) electrical interface. The transceiver shown in Figure 21 can be populated with HP's HFBR-14X4/24X6 820 nm components or HP's HFBR-1312T/2316T pin compatible 1300 nm components. When the transceiver shown in Figure 21 is populated with 820 nm components, and tested at a data rate of 155.5 MBd, using a 500 m length of 62.5/125 µm fiber, it provides a typical eye opening of 5.2 ns at a BER of 1 x 10^{-9}, as shown in Figure 20.

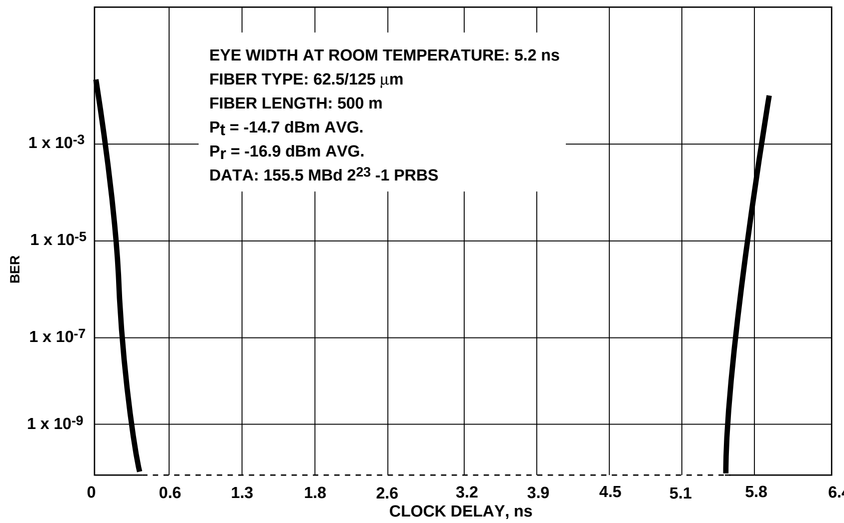

Figure 20. Typical BER vs. Clock Delay at 155.5 MBd.

The power supply filter and ECL terminations shown in Figure 22 are recommended for use with the transceiver shown in Figure 21. The printed circuit artwork for the surface mount transceiver is shown in Figure 23. A complete parts list for the 820 nm transceiver is shown in Table 1, and a complete parts list for the 1300 nm transceiver is shown in Table 2.

Designers interested in inexpensive solutions are encouraged to embed the complete fiber-optic transceiver described in this Application Note into the next generation of their new data communication products. All of the information needed to imbed the transceiver shown in Figure 21 can be obtained by calling the electronic bulletin board at 408-435-6733. Just call the bulletin board, then download the file named FURBALL.EXE to obtain electronic copies of the transceiver's artwork, schematic, and material list. If time to market is critical, the product development cycle can be shortened by ordering a fully assembled HFBR-0416 transceiver demo board from your local Agilent Field Sales Engineer.

References

[1] Agilent Technologies' Optoelectronics Designer's Catalog 1988, HFBR-AWSyyy data sheet.

[2] James J. Refi, "LED Bandwidth of Multimode Fibers as a Function of Laser Bandwidth and LED Spectral Characteristics", Journal of Lightwave Technology, Volume LT-4 No. 3, March 1986.

[3] Delon C. Hanson and Jerry Hutchison, "LED Source and Fiber Specification Issues for the FDDI Network", COMPCON Spring '87, IEEE Computer Society, (San Francisco, CA), February 24-26, 1987.

[4] Delon C. Hanson, "Fiber Optic Sub-System for Local Area Networks", OFC '88, (New Orleans, LA), January 24-28, 1988.

[5] Hans O. Sorensen, "Use of Standard Modulation Codes for Fiber Optic Link Optimization", FOC 1984.

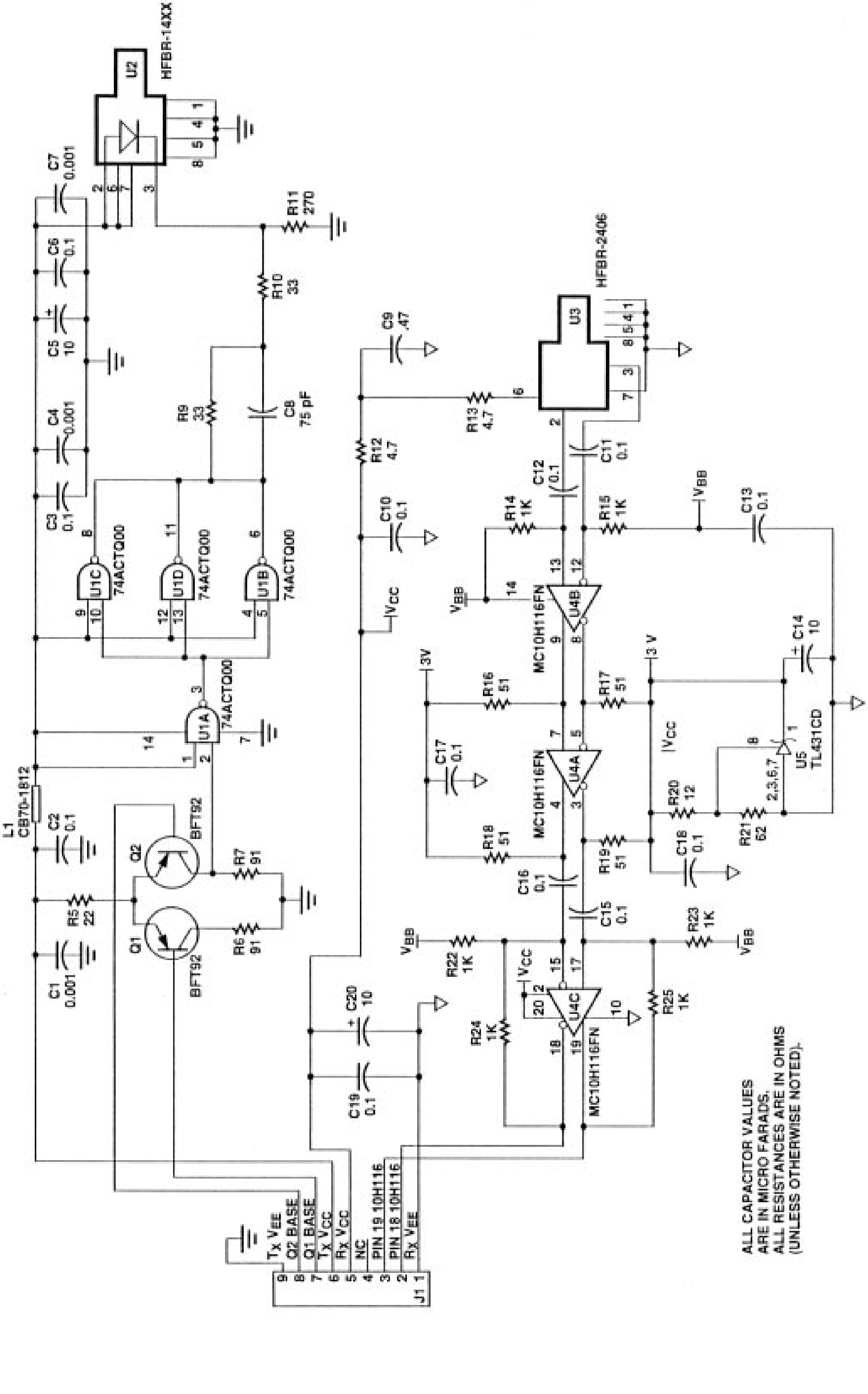

Figure 21. 155 MBd 1x9 Transceiver Schematic

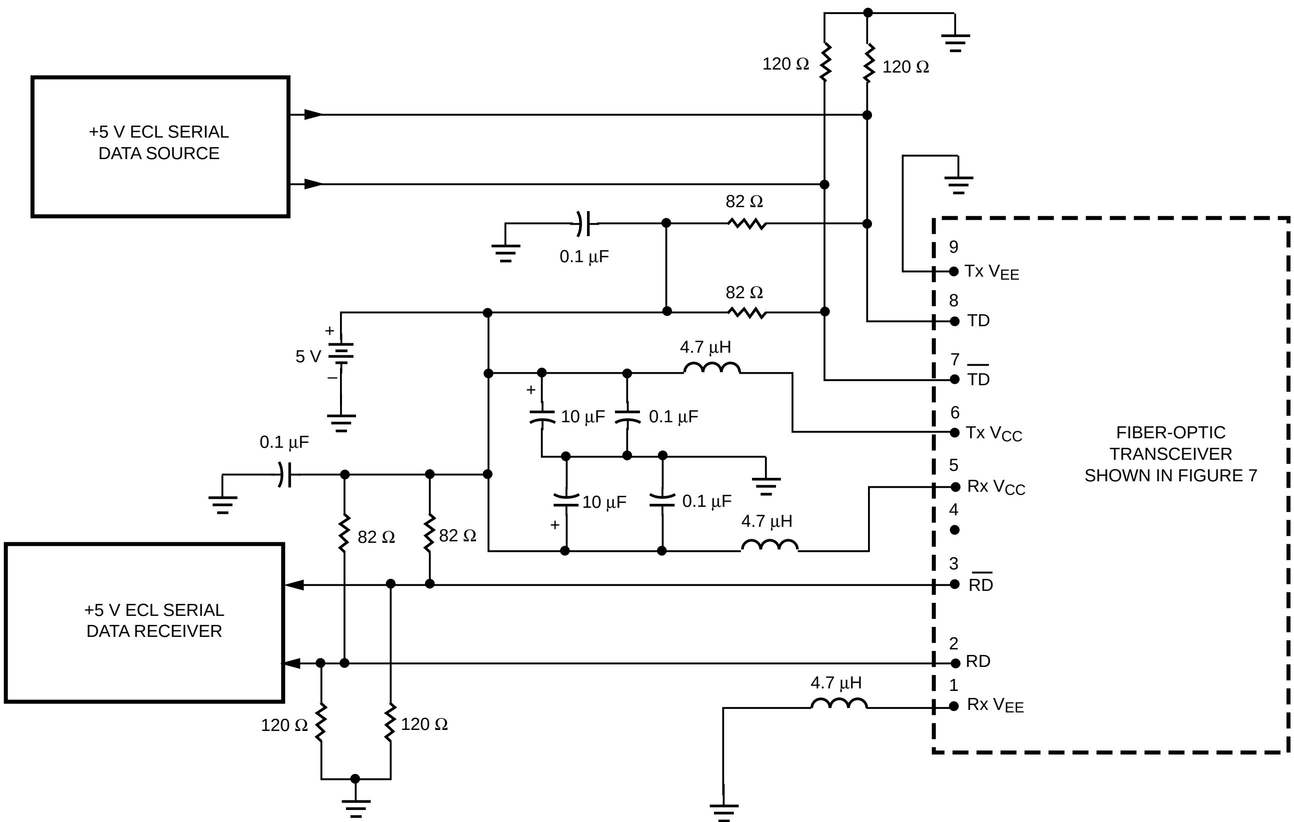

Figure 22. Recommended Power Supply Filter and +5 V ECL Signal Terminations

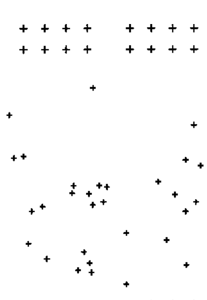

Figure 23a. Drill Drawing

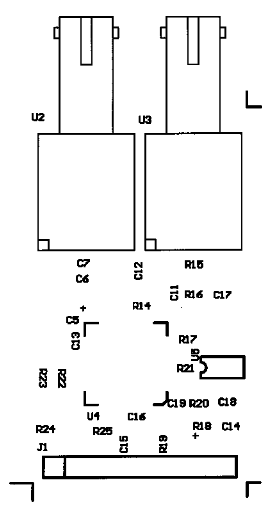

Figure 23b. Top Silkscreen

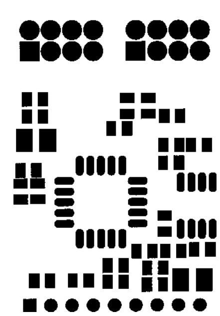

Figure 23c. Top Side Solder Mask

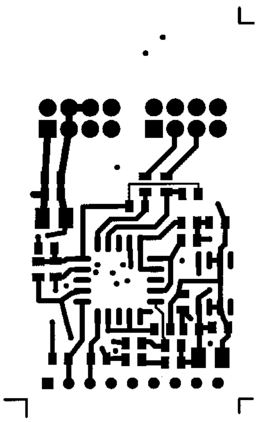

Figure 23d. Top Layer Copper

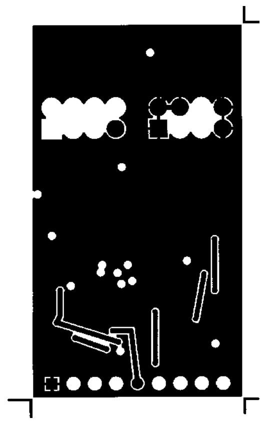

Figure 23e. Mid Layer (2) Rx GND

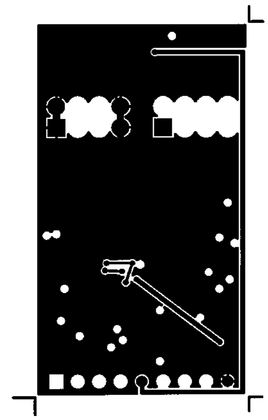

Figure 23f. Mid Layer (3) Ts GND

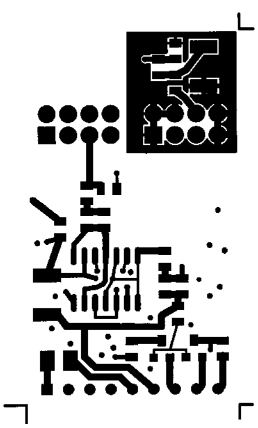

Figure 23g. Bottom Copper

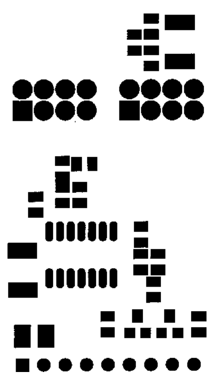

Figure 23h. Bottom Side Solder Mask

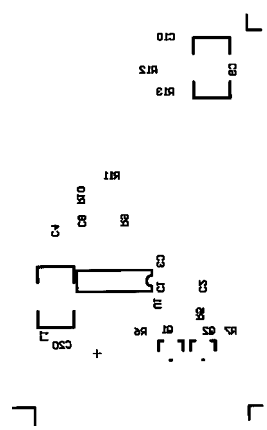

Figure 23i. Bottom Silkscreen

Table 1. Bill of Materials for Multi-Mode 820 nm Fiber-Optic Transceiver

DesIgnator	Part Type	Description	Footprint	Material	Part Number	Quantity	Vendor 1
C1	0.001	Capacitor	805	NPO/COG	C0805NPO500102JNE	3	Venkel
C4	0.001	Capacitor					
C7	0.001	Capacitor					
C10	0.1	Capacitor	805	X7R or better	C0805X7R500104KNE	12	Venkel
C 11	0.1	Capacitor					
C 12	0.1	Capacitor					
C 13	0.1	Capacitor					
C 15	0.1	Capacitor					
C 16	0.1	Capacitor					
C17	0.1	Capacitor					
C 18	0.1	Capacitor					
C 19	0.1	Capacitor					
C2	0.1	Capacitor					
C3	0.1	Capacitor					
C6	0 1	Capacitor					
C9	0.47	Capacitor	1812	X7R or better	C 1812X7R500474KNE	1	Venkel
C14	10	Capacitor	B	Tantalum, 10v	TA010TCM106MBN	3	Venkel
C20	10	Capacitor					
C5	10	Capacitor					
C8	75 pF	Capacitor	805	NPO/COG	C0805COG500750JNE	1	Venkel
U1	I.C.	Nand Gate	S08		74ACTQ00	1	National
U2	Fioer-Optic	Transmitter			HFBR-1414	1	HP
U3	Fiber-Optic	Receiver			HFBR-2416	1	HP
U4	MC10H116FN	IC, ECL line receiver	PLCC20		MC10H116FN	1	Motorola
U5	TL431CD	IC, Voltage Regulator	SO-8		TL431CD	1	T.I.
L1	CB70-1812	Inductor	1812		HF30ACB453215	1	TDK
R12	4.7	Resistor	805	5%	CR08051OW4R7JT	2	Venkel
R 13	4.7	Resistor					
R20	12	Resistor	805	5%	CR080510W120JT	1	Venkel
R9	33	Resistor	805	5%	CR080510W330JT	1	Venkel
R10	33	Resistor	805	5%	CR080510W330JT	1	Venkel
R11	270	Resistor	805	5%	CR080510W271JT	1	Venkel
R5	22	Resistor	805	5%	CR08051OW220JT	1	Venkel
R16	51	Resistor	805	5%	CR080510W510JT	4	Venkel
R17	51	Resistor					
R18	51	Resistor					
R19	51	Resistor					
R21	62	Resistor	805	5%	CR08051OW620JT	1	Venkel
R6	91	Resistor	805	5%	CR080510W91OJT	2	Venkel
R7	91	Resistor					
R14	1K	Resistor	805	5%	CR080510W102JT	6	Venkel
R15	1 K	Resistor					
R22	1 K	Resistor					
R23	1 K	Resistor					
R24	1 K	Resistor					
R25	1 K	Resistor					
Q1	BFT92	Transistor	SOT-23		BFT92	2	Philips
Q2	BFT92	Transistor					
J1		Pins			343B	9	McKenzie

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Table 2. Bill of Materials for Multi-Mode 1300 nm Fiber-Optic Transceiver

Designator	Part Type	Description	Footprint	Material	Part Number	Quantity	Vendor 1
C1 C4 C7	0.001 0.001 0.001	Capacitor Capacitor Capacitor	805	NPO/COG	C0805NPO500102JNE	3	Venkel
C10 C 11 C 12 C 13 C 15 C 16 C17 C 18 C 19 C2 C3 C6	0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0 1	Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor	805	X7R or better	C0805X7R500104KNE	12	Venkel
C9	0.47	Capacitor	1812	X7R or better	C 1812X7R500474KNE	1	Venkel
C14 C20 C5	10 10 10	Capacitor Capacitor Capacitor	B	Tantalum, 10v	TA010TCM106MBN	3	Venkel
C8	150 pF	Capacitor	805	NPO/COG	C0805COG500151JNE	1	Venkel
U1	I.C.	Nand Gate	S08		74ACTQ00	1	National
U2	Fioer-Optic	Transmitter			HFBR-1312T	1	HP
U3	Fiber-Optic	Receiver			HFBR-2316T	1	HP
U4	MC10H116FN	IC, ECL line receiver	PLCC20		MC10H116FN	1	Motorola
U5	TL431CD	IC, Voltage Regulator	SO-8		TL431CD	1	T.I.
L1	CB70-1812	Inductor	1812		HF30ACB453215	1	TDK
R12 R 13	4.7 4.7	Resistor Resistor	805	5%	CR08051OW4R7JT	2	Venkel
R20	12	Resistor	805	5%	CR080510W120JT	1	Venkel
R9	22	Resistor	805	5%	CR080510W220JT	1	Venkel
R10	27	Resistor	805	5%	CR080510W270JT	1	Venkel
R5	22	Resistor	805	5%	CR080510W220JT	1	Venkel
R16 R17 R18 R19	51 51 51 51	Resistor Resistor Resistor Resistor	805	5%	CR080510W510JT	4	Venkel
R21	62	Resistor	805	5%	CR08051OW620JT	1	Venkel
R6 R7	91 91	Resistor Resistor	805	5%	CR080510W91OJT	2	Venkel
R14 R15 R22 R23 R24 R25	1 K 1 K 1 K 1 K 1 K 1 K	Resistor Resistor Resistor Resistor Resistor Resistor	805	5%	CR080510W102JT	6	Venkel
Q1 Q2	BFT92 BFT92	Transistor Transistor	SOT-23		BFT92	2	Philips
J1		Pins			343B	9	McKenzie

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Data subject to change.

Obsoletes 5091-9102E

5965-6005E (11/99)