Agilent Technologies

Inexpensive 20 to 160 MBd Fiber-Optic Solutions for Industrial, Medical, Telecom, and Proprietary Data Communication Applications

Application Note 1123

Introduction

Low-cost fiber-optic data-communication links have been used in place of copper wire in numerous industrial, medical and proprietary applications. The fiber-optic transmitters and receivers shown in this publication can be used in a wide range of applications that convey encoded serial data provided by off-the-shelf, large-scale, mixed-signal integrated circuits such as the AMD TAXIchip ™, the Cypress HOTLink ™ or the PMC Sierra S/UNI-LITE ™. Byte-to-light solutions can be quickly implemented when these off-the-shelf serializer/deserializer circuits are combined with the fiber-optic transceivers described in this publication. Complete +5 V ECL (PECL)-compatible digital fiber-optic transceivers are presented in this application note. These complete solutions include the schematic, printed circuit artwork and material lists, so that users of this low-cost optical technology will not need to do any analog design. Designers interested in the recommendations contained in this publication are encouraged to imbed these reference designs in their products, and various methods for electronically down-loading these reference designs are described.

Why Use Optical Fibers?

Although copper wire is an established technology that has been successfully used to transmit data in a wide range of industrial, medical and proprietary applications, it can be difficult or impossible to use in numerous situations. By using differential line receivers or optocouplers, copper wires can be used to transmit data in applications where the reference or ground potentials of two systems are different, but care must be taken not to corrupt the data with noise induced into the metallic conductors or shields by adjacent power lines or differences in ground potential. Unlike copper wires, optical fibers do not require rigorous grounding rules to avoid ground loop interference, and optical transmission lines do not need termination resistors to avoid reflections. Optical transceivers and cables can be designed into systems so that they will survive lightning strikes that would normally damage metallic conductors or wire input/output (I/O) cards. In essence, fiber-optic data links are used in electrically noisy environments where copper wire fails.

In addition to all of these inherent advantages, there are two other reasons why optical fibers are beginning to replace copper wires. The first reason is that optical connectors suited for field installation with minimal training and simple tools are now available. The second reason is that when using plastic optical fiber (POF) or hard clad silica (HCS) fiber, the total cost of the data communication link is roughly the same as when using copper wires.

Communication Protocols and Optical Data Links

Many existing serial communication protocols were developed for use with copper wire. At data rates below 30 Mbits/second, copper wire has routinely been used with differential line receivers or optocouplers that can sense the dc component of binary data communication signals. This type of serial data is often called “arbitrary duty factor” data because it can remain in the logic “1” or logic “0” state for indefinite periods of time. Arbitrary duty factor data has an average value, which can instantaneously be anywhere between 0 percent and 100 percent of the binary signal’s amplitude, or in other words, arbitrary duty factor data contains dc components. Communication protocols that were developed specifically for use with copper wire often require an optical receiver that is dc coupled or capable of detecting if the data is changing from a high-to-low or low-to-high logic state, that is, the receiver needs to be an edge detector. At relatively modest data rates between zero and 10 Mbits/sec it is possible to construct dc coupled TTL-compatible fiber-optic receivers. The Agilent HFBR-2521 is a TTL-compatible, dc-to-5 Mbit/sec receiver, and the HFBR-2528 is a dc-to-10 Mbit/sec CMOS or TTL-compatible receiver. Additional information about dc-to-5 Mbit/sec applications can be found in Hewlett-Packard AN-1035, and applications support for dc-to-10 Mbit/sec applications can be obtained by reading AN-1080. This application note focuses on optical data communication links that operate at much higher data rates and much greater distances than achievable with the dc-coupled or edge-detecting fiber-optic receivers. The optical transceivers shown in this application note are intended for use with parallel data that has been replaced by serialized encoded symbols. When encoding is used, the average value of the serial data is equal to approximately 50 percent of the serialized data's amplitude. If your communication system sends unencoded or burst-mode data where the average value of the serial data can arbitrarily be anywhere between 0 percent to 100 percent of the binary signal's amplitude, please refer to the solutions provided in Agilent Application Note 1121.

Advantages of Encoded Run-Limited Data

As the data rate of a digital communication link increases, the reasons for encoding the raw data become more compelling. When data is encoded, the original data bits are replaced with a different group of bits known as symbols. The symbols that replace the original data are selected so that the encoded data is compatible with simple, highly sensitive, ac-coupled fiber-optic receivers. Encoding enables the construction of optimal fiber-optic receivers which are limited by the random noise inherent in the receiver's first amplifier stage. Noise-limited ac-coupled receivers can provide very low error rates when used with long optical fibers, or can be useful in applications that utilize optical splitters having large amounts of fixed optical losses.

Data is encoded to prevent the digital information from remaining in one of the two possible logic states for an indefinite period of time. When data is encoded, a characteristic known as the "run limit" is established. If data is not changing, the run limit defines how much time may pass before the encoder inserts a transition from one logic state to another. The run length, or run limit of the encoder, is the number of symbol periods that are allowed to pass before the encoder changes logic state. Encoders usually force the encoded data to have a 50 percent duty factor, or they restrict the duty factor to a limited range, such as 40 percent to 60 percent. When data is encoded, the fiber-optic receiver can be ac-coupled as shown in Figure 1. Without encoding, the fiber-optic receiver would need to detect dc levels, or edges, to determine the proper logic state during long periods of inactivity when there are no changes in the transmitted data. AC-coupled fiber-optic receivers tend to be lower in cost, are much easier to design, provide better sensitivity and contain fewer components than their dc-coupled counterparts.

No matter which type of fiber-optic media is used, the receiver's PIN pre-amplifier should be ac-coupled to a limiting amplifier and comparator as shown in Figure 1. Direct coupling decreases the sensitivity of a digital fiber-optic receiver, since it allows low-frequency flicker noise from transistor amplifiers to be presented to the receiver's 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 the sensitivity of the fiber-optic receiver.

Another problem associated with direct-coupled receivers is the accumulation of dc offsets. With direct coupling, the receiver's gain stages amplify the effects of undesirable offsets and voltage drifts due to temperature changes. These amplified dc offsets will eventually be applied to the comparator and 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's 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 logic states. Problems with

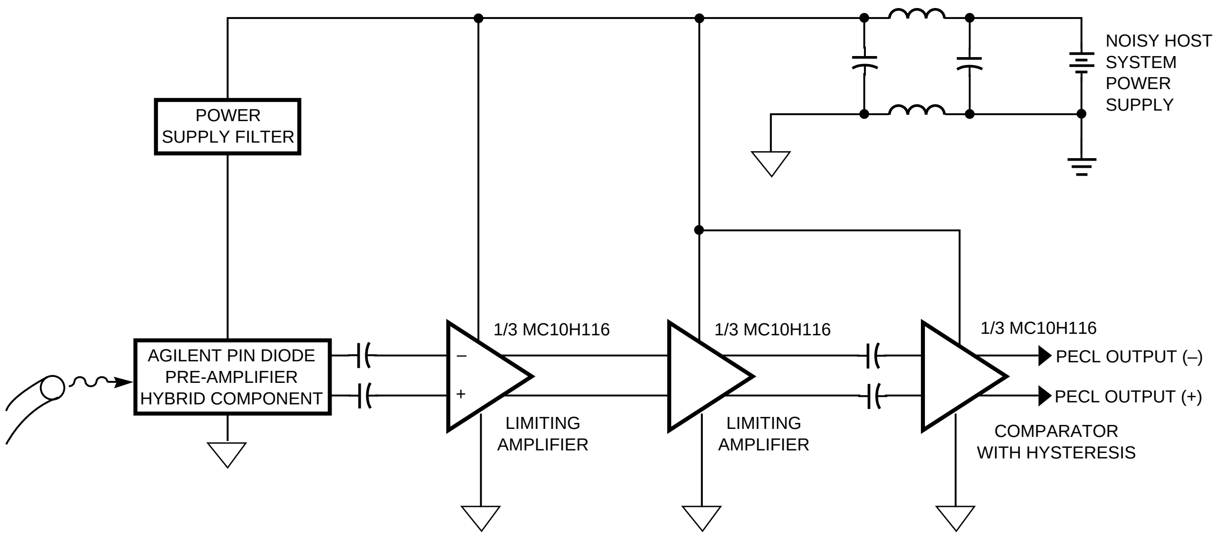

Figure 1. Simplified +5 Volt ECL (PECL-compatible) Fiber-optic Receiver Block Diagram for High Data Rate Applications with Encoded Data

dc drift can be avoided by constructing the receiver as shown in Figure 1.

Encoding has other advantages. Encoding merges the data and clock signals in a manner that allows a timing-recovery circuit to reconstruct the clock at the receiver end of the digital data link. This is essential because fiber-optic links can send data at such high rates that asynchronous timing-recovery techniques, such as over-sampling, are not very practical. Synchronous detection can be accomplished without encoding, but the clock signal required to synchronously detect the data would need to be sent via a second fiber-optic link. Separate transmission channels for data and clock signals are usually avoided due to cost, but problems with time skew between the data and clock can also arise if separate fibers are used to transmit these signals.

Characteristics of Encoders

A Manchester encoder replaces each bit with two symbols. For instance, when using Manchester code a logic “1” is replaced by a (“1”, “0”) symbol, and a logic “0” is replaced by a (“0”, “1”) symbol. Manchester code is not very efficient since it doubles the fundamental frequency of the data by substituting two symbols for each bit transmitted. Block substitution codes such as 4B5B replace four bit nibbles of data with a five bit symbol. Other popular block substitution codes are also used. A 5B6B encoder replaces each group of five bits with a six bit symbol and an 8B10B encoder replaces an entire eight bit byte with 10 symbols. Block substitution codes encode the data more efficiently. If Manchester code is used to transmit data at 100 Mbits/second, the fiber-optic channel must be capable of passing 200 million symbols/second. Baud (Bd) is expressed in units of symbols/second, thus the Manchester encoder in this example requires a serial data link that can work at 200 MBd. If the less efficient Manchester encoder is replaced by a more efficient 4B5B encoder, the same 100 Mbit/second data can be sent at a signaling rate of 125 MBd. In binary transmission systems, the maximum fundamental frequency of the data is half the symbol rate expressed in Bd. When a Manchester encoder is used to send 100 M bit/second data, at a symbol rate of 200 MBd, the maximum fundamental frequency of the data is 100 MHz. By using a 4B5B encoder, the same 100 Mbit/second data can be transmitted at 125 MBd, at a maximum fundamental frequency of 62.5 MHz.

The minimum fundamental frequency that the fiber-optic link must pass is also determined by the encoding rule chosen. The run limit of the encoder determines the maximum number of symbol periods that the encoder will allow before it forces a transition,

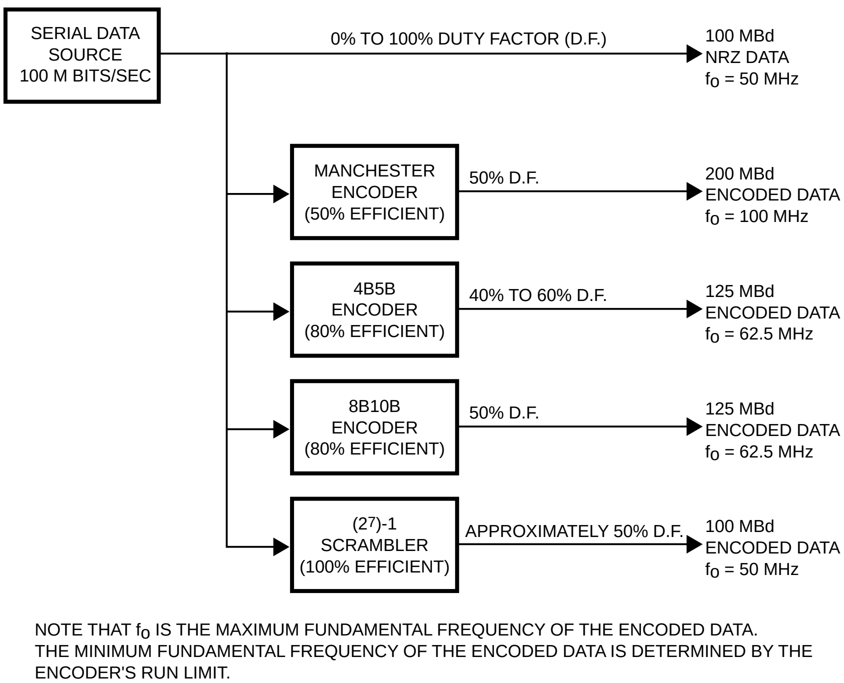

Figure 2. Attributes of Encoding

thus the encoder's run limit determines the minimum fundamental frequency of the encoded data. Manchester code will allow only two symbol periods to pass without a transition. As many as three symbol times without a transition will be allowed by the 4B5B encoder used in the AMD TAXIchip™.

Figure 2 illustrates the attributes of various encoding techniques. Figure 2 shows that as encoder efficiency improves, the bandwidth needed in the fiber-optic communication channel is reduced. Conversely, for a fixed communication channel bandwidth the number of bits/second that can be transmitted will increase as encoder efficiency improves.

Off-the-Shelf Parallel-to-Serial and Serial-to-Parallel Converter Chips

Large scale integrated physical layer circuits (PHY chips) such as the AMD TAXIchip, CYPRESS HOTLink and PMC Sierra S/UNI LITE do more than encode the data. Modern PHY chips provide the digital and analog functions needed to transform the parallel data found in virtually all parallel architecture computer-based systems to the serial data needed for transmission via an optical fiber communication link. The mixed-signal LSI chip at the transmitting end of the fiber-optic link synthesizes a high-frequency clock from the host system's byte-rate clock, multiplexes parallel TTL data to serial data and provides the control words and synchronizing signals needed to manage a serial data communication link. The mixed-signal LSI chip at the receiving end contains a phase-locked loop to recover the clock signal imbedded in the received serial data, a decoder to strip off the encoding, plus a demultiplexer that converts the serial data and control signals back to a parallel TTL output. The high-speed serial inputs and outputs of most PHY chips are compatible with +5V ECL (PECL) logic. Since the fiber-optic transceiver described in this application note has PECL-compatible inputs and outputs, it can be easily combined with the TAXIchip, HOTLink or S/UNI-LITE chips to build byte-to-light communication systems.

Only One Transceiver Design Needed

This application note will show that various Agilent LED transmitters and PIN-diode pre-amplifiers can be used in a single transceiver design that can be electronically down-loaded and imbedded into a wide range of products to provide very low-cost data communication solutions. Without changing the form-factor or printed circuit design, the transceiver shown in this publication can be populated with components that can send digital data via plastic optical fiber, hard clad silica fiber, multimode glass fiber or single-mode glass fiber. When these schematics and printed circuit artworks are electronically imported and imbedded into your system, the same inexpensive transceiver circuit can be used with a wide variety of fiber-optic cables so that one design can be used to address an extremely wide range of data communication applications.

Distances Achievable at Data Rates up to 160 MBd

The simple transceivers recommended in this application can be used to address a very wide range of distances, data rates and system cost targets. The maximum distances allowed with various types of optical fiber and Agilent's wide range of fiber-optic transceiver components are shown Table 1. No transmitter or receiver adjustments are needed when using fiber cable lengths that vary from virtually zero length up to the maximum distances specified in Table 1.

Simple PECL-Compatible LED Transmitter

A high-performance, low-cost PECL-compatible transmitter is shown in Figure 3. This transmitter recommendation looks deceptively simple but has been highly developed to deliver the best performance achievable with a wide range of Agilent LED transmitters. The recommended transmitter is also very inexpensive since the 74ACTQ00 gate that modulates the current of the various LED transmitters can typically be obtained for under $0.40. No calculations are needed to determine the passive component needed when using various Agilent LEDs and various optical fibers. Simply use the recommended component values shown in Table 2, and the transmitter shown in Figure 3 can be used to address a wide range of applications.

Simple High-Sensitivity PECL-Compatible Receiver

A very simple PECL-compatible receiver with excellent sensitivity and suited for a wide range of applications is shown in Figure 4. The receiver in Figure 4 is optimal for operation at any data rate between 20 and 160 MBd. A single low-cost 10H116 ECL line receiver is used to amplify and digitize the output of the Agilent PIN diode pre-amp component, which functions as the receiver's first stage. The third section of the 10H116 integrated circuit is configured to provide hysteresis, so that when no light is applied to the receiver's optical input the digital output of the receiver will not chatter. The simple low-cost circuit shown in Figure 4 provides excellent sensitivity, adequate for many applications. Some data communication protocols however require that the optical receiver provide an optical link status flag (also known as signal detect) that switches state when received power is low, or the optical fiber is disconnected. An alternative receiver that provides this signal detect function is shown in Figure 5. Both receiver circuits have similar relationships between sensitivity, and error rate, since the random noise from the Agilent PIN diode pre-amp used in the first stage has a dominant effect upon the receiver's performance.

Table 1

LED Transmitter Component Part # and Wavelength	Receiver Component Part # and Wavelength	Fiber Diameter Type	Maximum Distance at 160 MBd with the transceiver circuits recommended in this publication
HFBR-15X7 650 nm	HFBR-25X6 650 nm	1 mm plastic step index NA = 0.35	50 meters with the transceiver in Fig. 7 or Fig. 8
HFBR-15X7 650 nm	HFBR-25X6 650 nm	200 µm HCS step index NA = 0.37	50 meters with the transceiver in Fig. 7 or Fig. 8
HFBR-14X2 820 nm	HFBR-24X6 820 nm	200 µm HCS step index = 0.37	50 meters with the transceiver in Fig. 7 or Fig. 8
HFBR-14X4 820 nm	HFBR-24X6 820 nm	62.5/125 µm multimode glass	500 meters with the transceiver in Fig. 7 or Fig. 8
HFBR-13X2 1300 nm	HFBR-23X6 1300 nm	62.5/125 µm multimode glass	2 kilometers with the transceiver in Fig. 7 or Fig. 8
HFBR-1315 1300 nm	HFBR-2315 1300 nm	9/125 µm single-mode glass	6 kilometers with the transceiver in Fig. 7 or Fig. 8

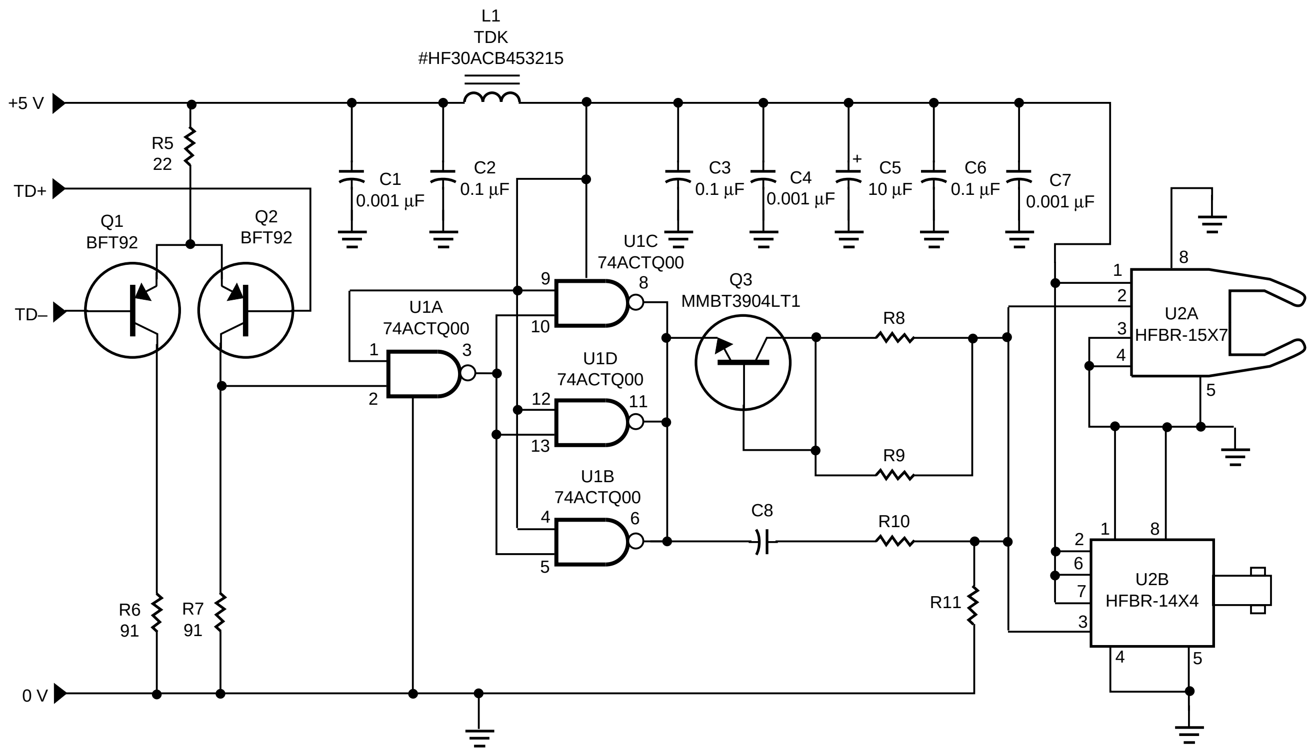

Figure 3. +5 V ECL (PECL-compatible) 160 MBd Fiber-optic Transmitter

Table 2

Transmitter	HFBR-15X7 650 nm LED		HFBR-14X2 820 nm LED	HFBR-14X4 820 nm LED	HFBR-13X2 1300 nm LED	HFBR-13X5 1300 nm ELED
Fiber Type	1 mm Plastic	200 µm HCS	200 µm HCS	62.5/125 µm	62.5/125 µm	9/125 µm
R8	301 Ω	82.5 Ω	300 Ω	84.5 Ω	78.7 Ω	53.6 Ω
R9	301 Ω	82.5 Ω	300 Ω	84.5 Ω	78.7 Ω	53.6 Ω
R10	15 Ω	15 Ω	82 Ω	56 Ω	47 Ω	33 Ω
R11	1 kΩ	475 Ω	2.2 kΩ	2.2 kΩ	∞	1.2 kΩ
C8	43 pF	120 pF	18 pF	33 pF	56 pF	56 pF

A Complete Fiber-Optic Transceiver Solution

Figure 6 shows the schematic for a complete fiber-optic transceiver. This transceiver is constructed on a printed circuit, which is 1" wide by 1.97" long, using surface-mount components. When the transceiver shown in Figure 6 is tested at a data rate of 155.5 MBd, using a 50 m length of 1 mm diameter plastic optical fiber with a numerical aperture (N.A.) of 0.33, it provides a typical eye opening of 3.6 ns at a BER of ≤ $1.1x10^{-10}$. Designers interested in inexpensive solutions are encouraged to embed the complete fiber-optic transceiver described in this application note into the next generation of new data communication products. The circuit in Figure 6 matches the electrical functions of industry-standard 1300 nm transceiver modules, with the exception that there is no signal-detect function in the Figure 6 circuit (pin 4 is nonfunctional). If your system's protocol requires a signal-detect feature, the transceiver shown in Figure 7 will provide it. The transceiver circuits shown in Figure 6 or Figure 7 can be directly inserted into boards designed for industry-standard fiber-optic transceivers modules with a 1X9 footprint and used as a cost-effective alternative in industrial, medical, telecom and proprietary data communication applications.

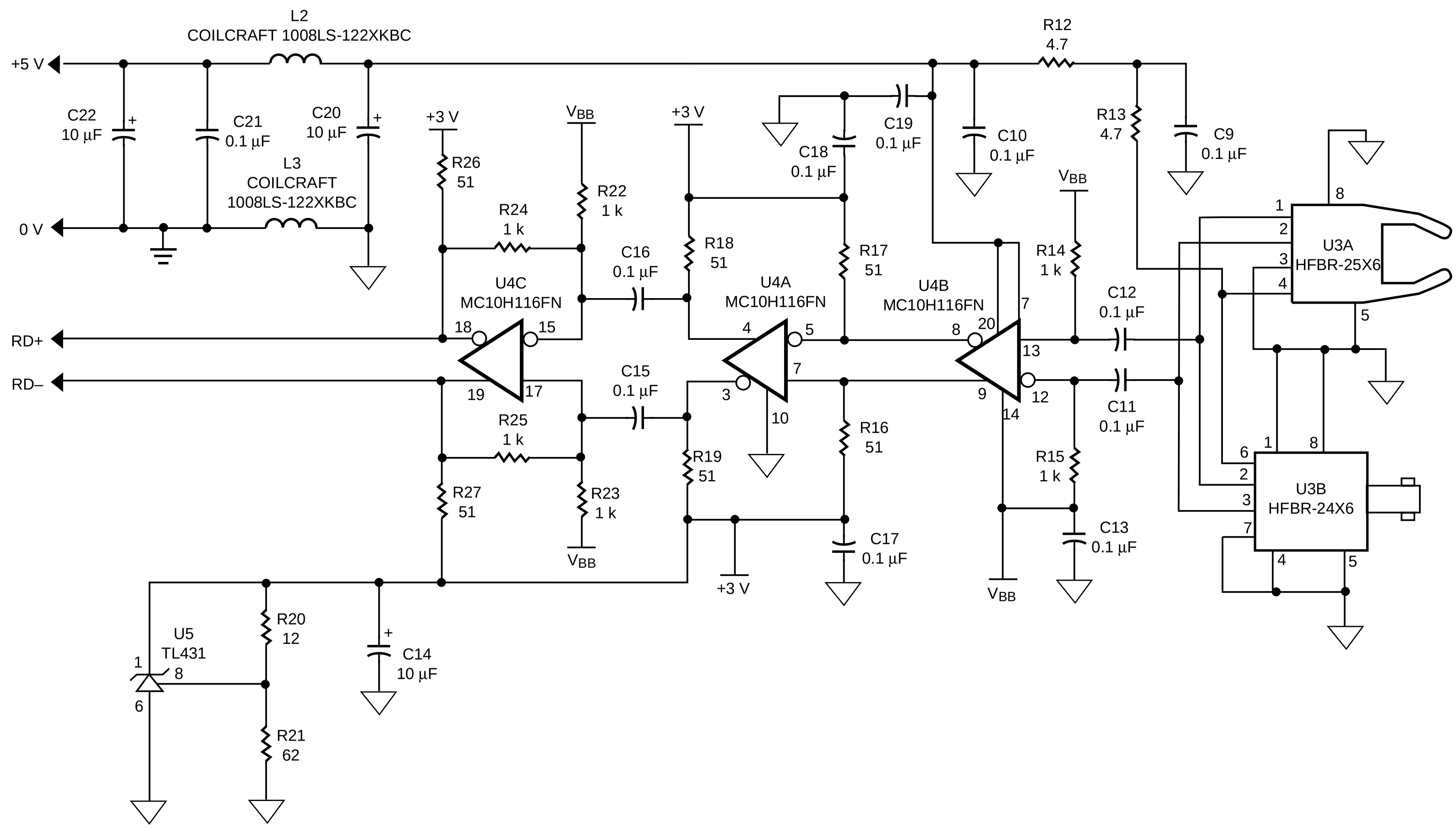

Figure 4. +5 V ECL (PECL-compatible) 160 MBd Fiber-optic Receiver

Table 3

Receiver	HFBR-25X6 650 nm		HFBR-24X6 820 nm	HFBR-23X6 1300 nm	HFBR-2315 1300 nm
Fiber Type	1 mm Plastic	200 µm HCS	62.5/125 µm	62.5/125 µm	9/125 µm

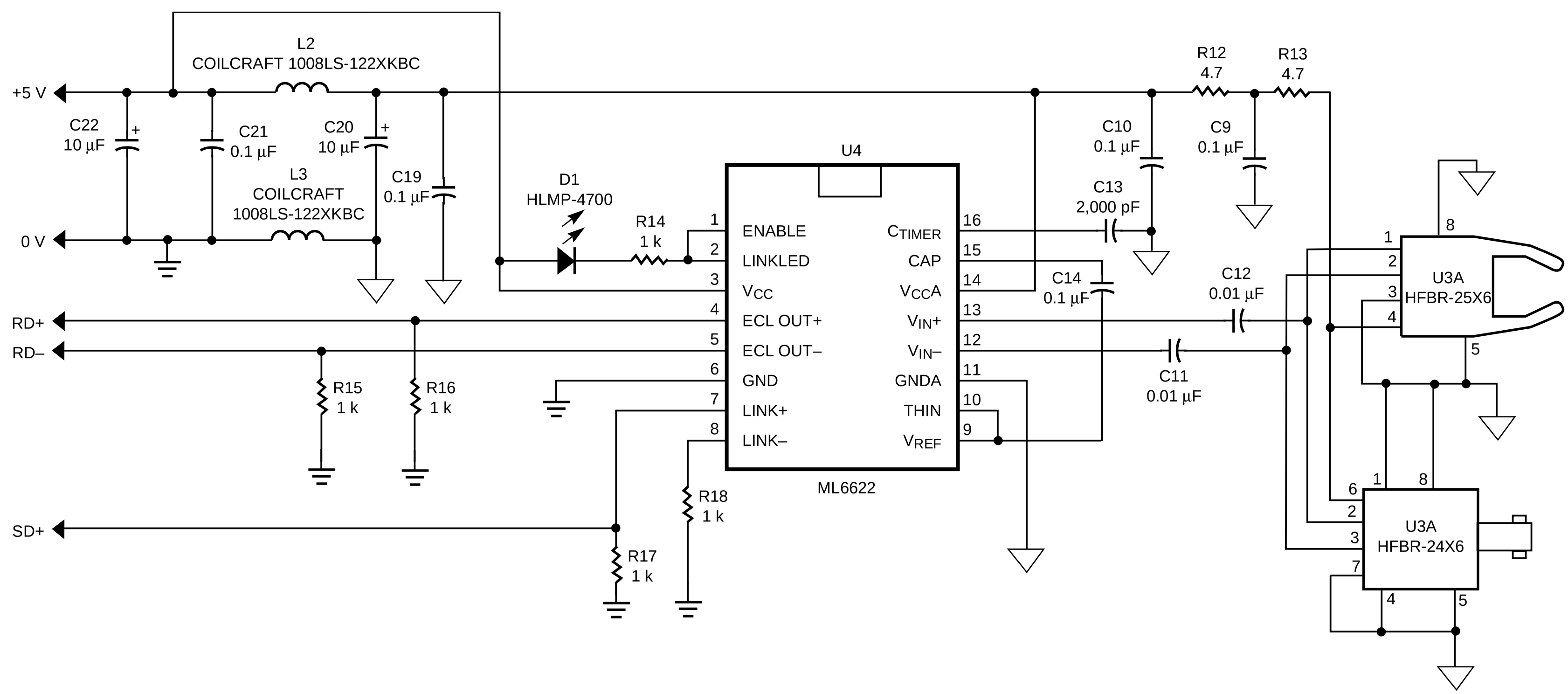

Figure 5. PECL-compatible 160 MBd Fiber-optic Receiver with Signal-Detect Function

Table 4

Receiver	HFBR-25X6 650 nm		HFBR-24X6 820 nm	HFBR-23X6 1300 nm	HFBR-2315 1300 nm
Fiber Type	1 mm Plastic	200 µm HCS	62.5/125 µm	62.5/125 µm	9/125 µm

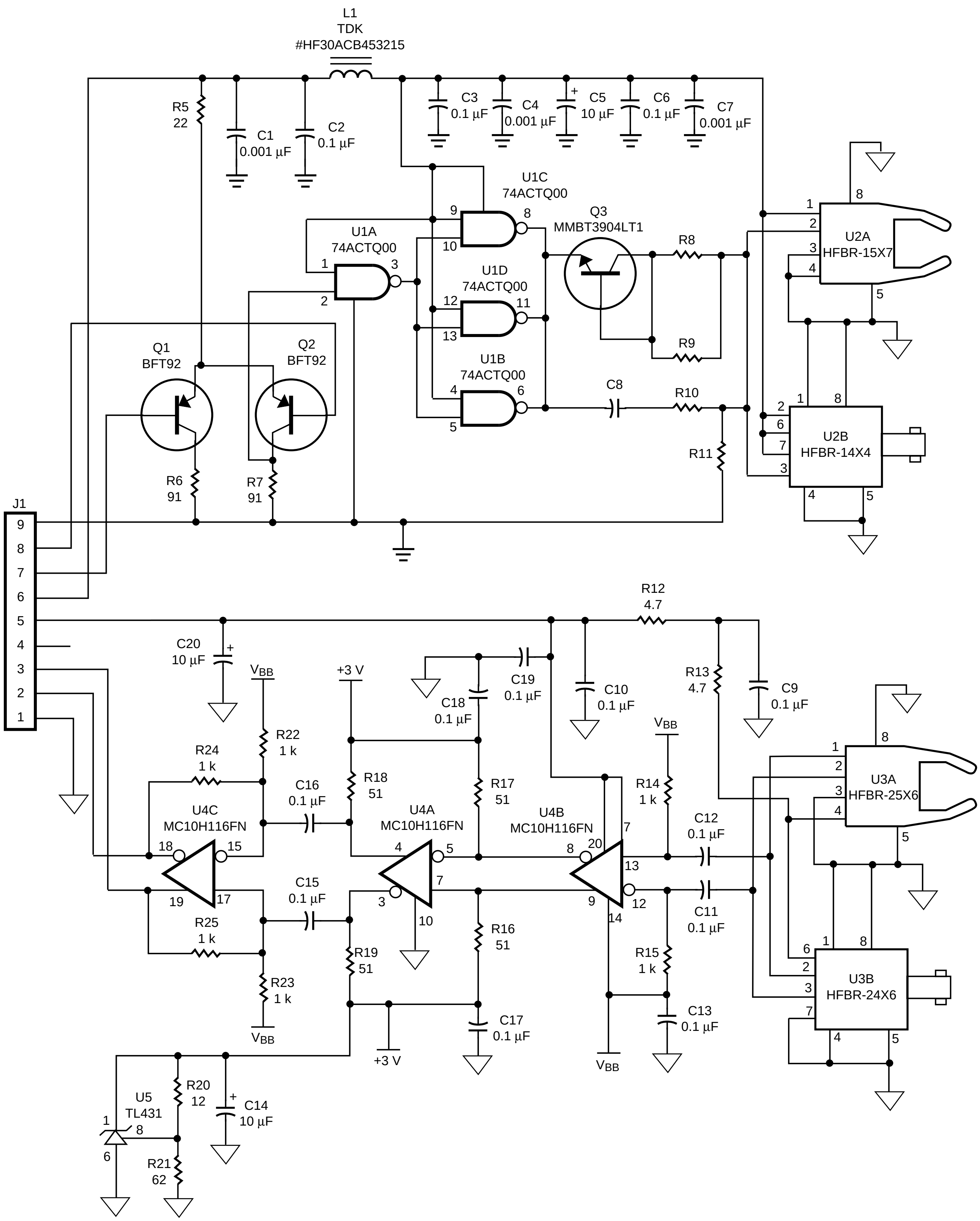

Figure 6. Lowest Cost 160 MBd Fiber-optic Transceiver

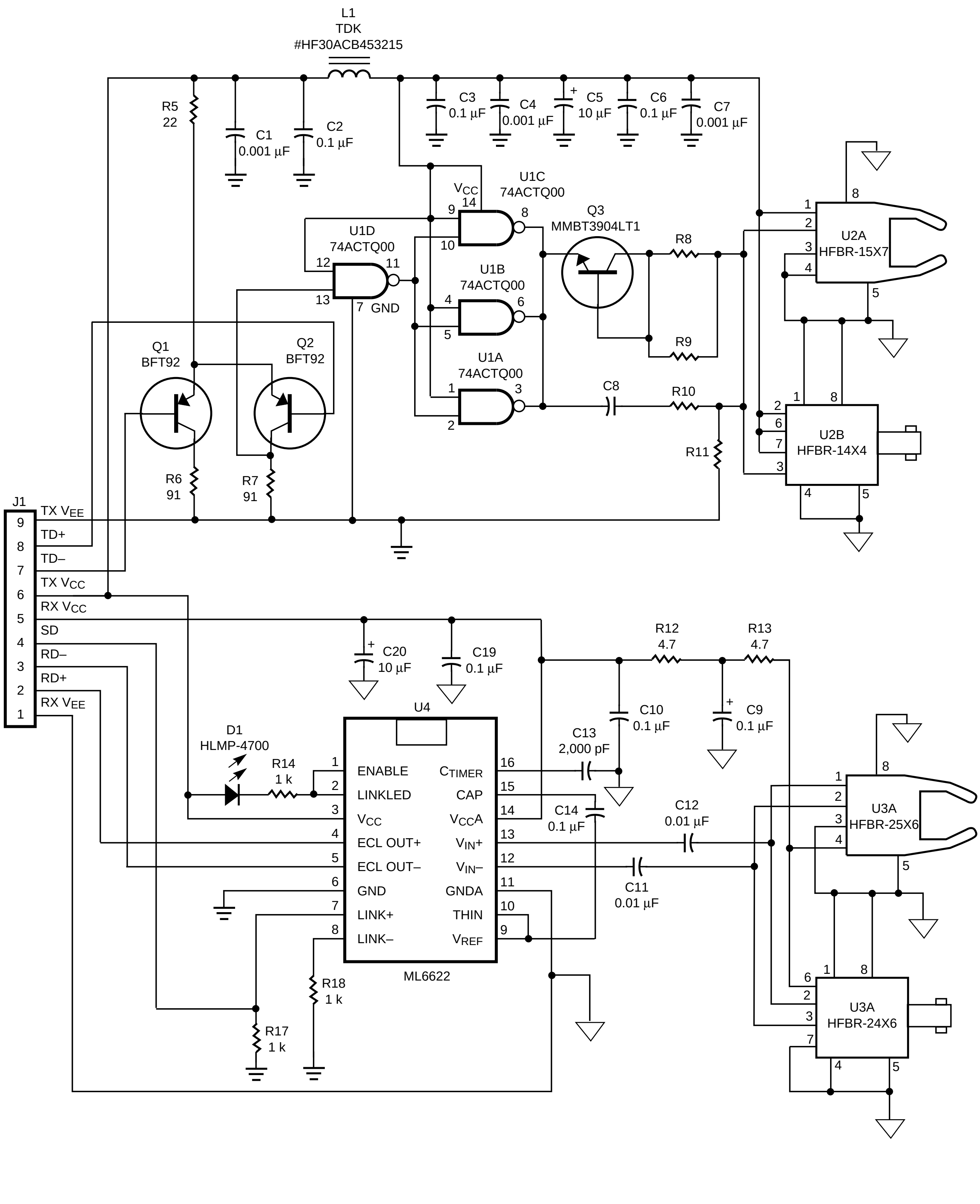

Figure 7. Full-featured 160 MBd Fiber-optic Transceiver with Signal-Detect Function

Signal Terminations and Power Supply Filtering Requirements

If the proper signal terminations and power supply filter circuits are used, the transceiver circuits in Figure 6 and Figure 7 have been proven to provide excellent performance. When using serializer and deserializer chips that provide PECL-compatible high-speed serial inputs and outputs, the power supply filter and terminations shown in Figure 8 are required. The signal terminations and power supply filtering shown in Figure 9 are required if the fiber-optic transceivers recommended in this application note are used with the PMC-Sierra PM5946 S/UNI-LITE chip for SONET OC-3 applications.

Error Rates and Noise Immunity

The probability that a fiber-optic link will make an error is related to the receiver's own internal random noise and the receiver's ability to reject noise originating from the system in which it is installed. The total noise present in any fiber-optic receiver is normally the sum of the PIN diode pre-amplifier's noise and the host

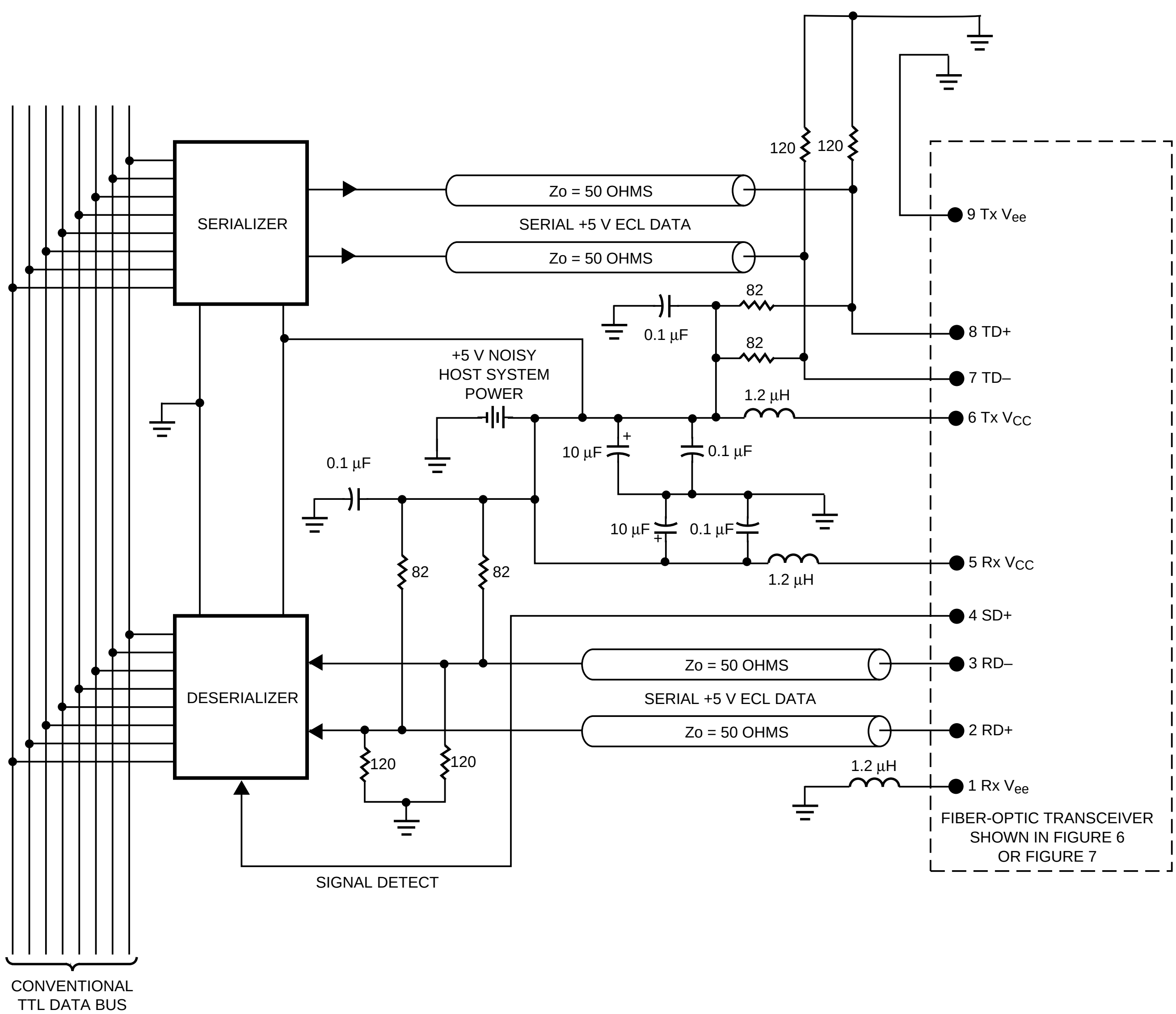

Figure 8. Recommended Power Supply Filter and +5 V ECL (PECL) Signal Terminations for the AMD TAXIchip™ and Cypress HOTLink™

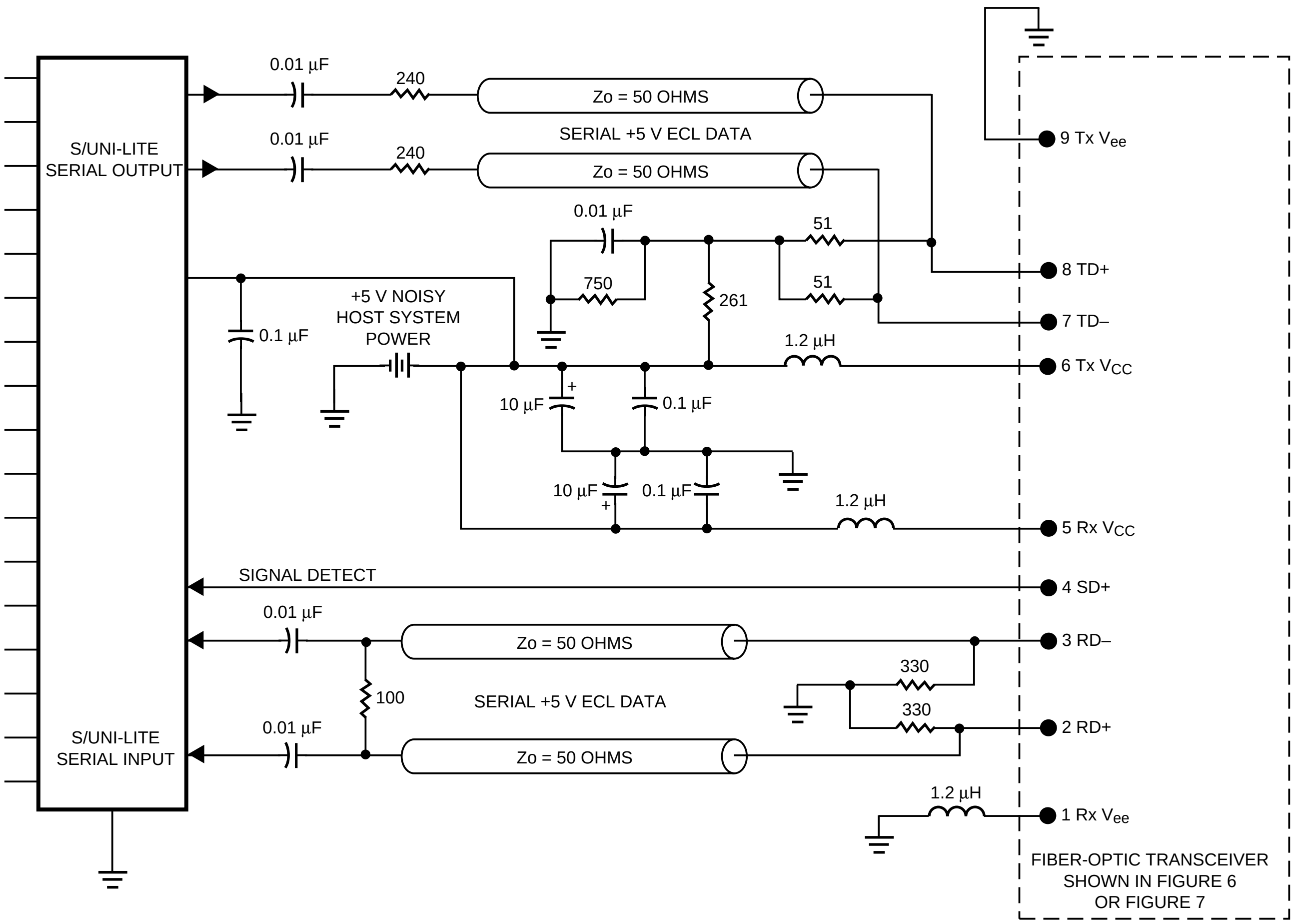

Figure 9. Recommended Power Supply Filter and +5 V ECL (PECL) Signal Terminations for the PMC-Sierra PM5946 S/UNI-LITE™

system's electrical noise. As the optical signal applied to the receiver increases, the probability that the receiver's total noise will alter the data decreases. Small increases in the receiver's signal-to-noise ratio will result in a very sharp reduction in the probability of error. Figure 10 shows that the receiver's probability of error is reduced by 6 orders of magnitude (from $1x10^{-9}$ to $1x10^{-15}$) when the receiver's signal-to-noise ratio improves from 12:1 to 15.8:1.

At any fixed temperature, the total value of the receiver's random noise plus the host system's noise can be assumed to be a constant, so the most obvious way to reduce the probability of error is to increase the amplitude of the optical signal applied to the receiver. A less obvious technique for lowering the error rate is to improve the receiver's ability to reject electrical noise from the system in which it resides. The fiber-optic receivers recommended in this application note have sufficient noise immunity to be used in most systems without electrostatic shielding. The Agilent PIN diode pre-amps, which are used in the receiver's first stage, are physically small hybrid circuits, and they do not function as particularly effective antennas. For

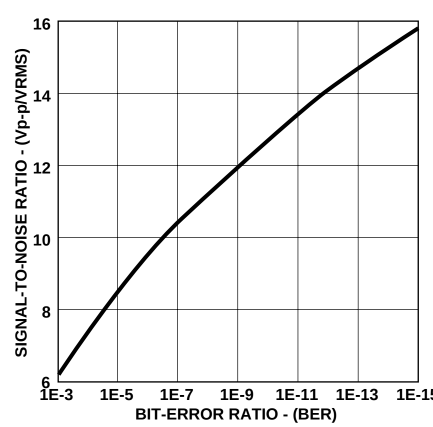

Figure 10. Receiver Signal-to-Noise Ratio vs. Probability of Error (aka BER)

extremely noisy applications, Agilent offers PIN diode pre-amps in electrically conductive plastic or metal packages. Agilent manufactures a wide range conductive and non-conductive fiber-optic components that mate with various industry standard fiber-optic connectors, but the overwhelming majority of the fiber-optic applications successfully implemented with Agilent's fiber-optic components have not required conductive plastic or metal receiver housings.

The most insidious and the most overlooked source of noise is usually the host system's +5V power supply. The host system's +5 volt supply normally powers the fiber-optic receiver, the fiber-optic transmitter and an entire system comprised of relatively noisy digital circuits. The simple and inexpensive power supply filters shown in Figure 8 and Figure 9 of this publication have been proven to work in a wide range of system applications and these recommended power supply filters are normally sufficient to protect the fiber-optic receiver from very noisy host systems.

Printed Circuit Artwork

The performance of transceivers that use Agilent fiber-optic components are partially dependent on the layout of the printed circuit board on which the transceiver circuits are constructed. To achieve the fiber-optic link performance described in Table 1 system designers are encouraged to imbed the printed circuit design provided in this application note. The printed circuit artwork in Figure 11 is for the transceiver shown in Figure 6. If your system requires a fiber-optic receiver with a signal-detect feature, the artwork shown in Figure 12 can be used to construct the transceiver shown in Figure 7.

Parts List

The PECL-compatible fiber-optic transceivers recommended in this publication are very simple and inexpensive, so only a few external components are needed. Complete parts lists are provided in Table 5 and Table 6. All of the components are compatible with the printed circuit artworks shown in Figures 11 and 12, thus minimizing the design time and resources needed to use the low cost fiber-optic transceivers shown in this application note.

Conclusion

The complete PECL-compatible fiber-optic transceiver solutions provided in this publication can be used to build new data communication systems that work at higher data rates and provide better noise immunity than possible with copper wire. When fiber-optic media is used in place of conventional copper wire, it is possible to build new communication systems that are immune to large noise transients caused by utility power switch gear, motor drives or high-voltage power supplies. Furthermore, the non-conductive cables used in optical communication links have an intrinsically higher probability of surviving lightning strikes than copper wire alternatives. The optical data communication solutions shown in this application note can also send high-speed, 160 MBd data over long distances impossible with copper wire cables. By imbedding the complete solutions shown in this application note, system designers can quickly develop a new generation of high-speed, noise-immune, optical communication links in a very short time with minimal research and development costs.

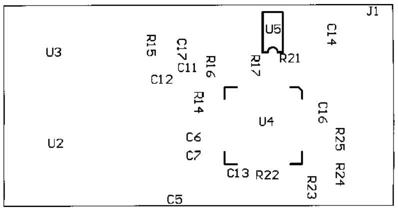

Figure 11a. Top Overlay

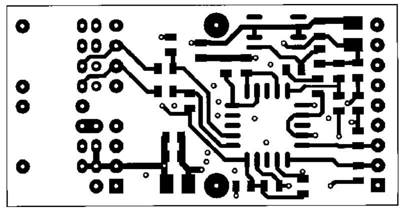

Figure 11b. Top Layer

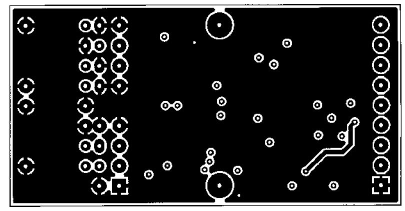

Figure 11c. Mid Layer 2

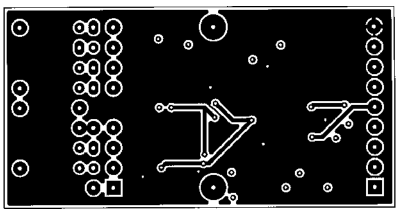

Figure 11d. Mid Layer 3

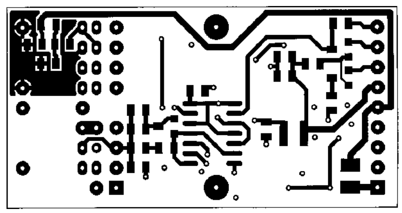

Figure 11e. Bottom Layer

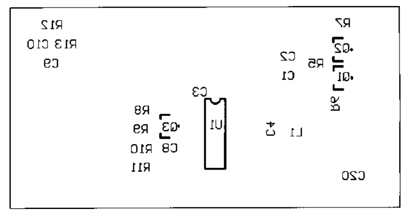

Figure 11f. Bottom Overlay

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Figure 11. Printed Circuit Artwork for Transceiver shown in Figure 6

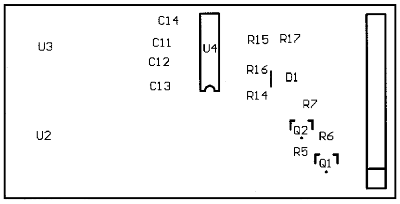

Figure 12a. Top Overlay

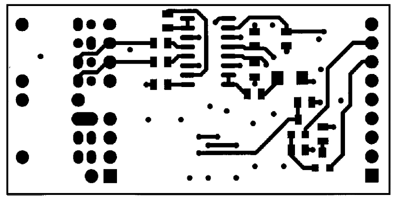

Figure 12b. Top Layer

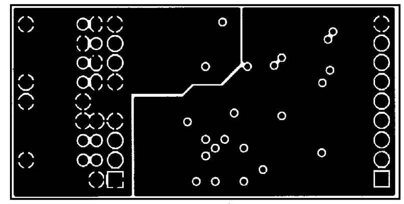

Figure 12c. Mid Layer 2

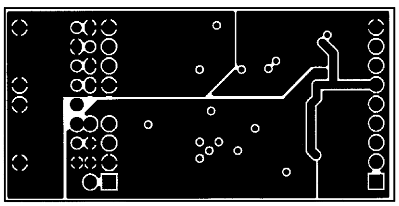

Figure 12d. Mid Layer 3

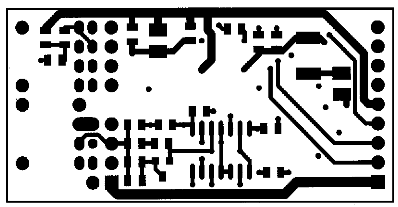

Figure 12e. Bottom Layer

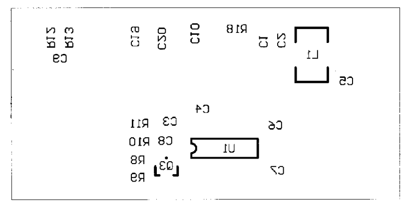

Figure 12f. Bottom Overlay

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Figure 12. Printed Circuit Artwork for Transceiver shown in Figure 7

Table 5. Parts List for the Transceiver in Figure 6

Designator	Part Type	Description	Footprint	Material	Part Number	Quantity	Vendor 1
C1 C4 C7	0.001 µF 0.001 µF 0.001 µF	Capacitor Capacitor Capacitor	805	NPO/COG	C0805NPO500102JNE	3	Venkel
C10 C11 C12 C13 C15 C16 C17 C18 C19 C2 C3 C6 C9	0.1 µF 0.1 µF 0.1 µF 0.1 µF 0.1 µF 0.1 µF 0.1 µF 0.1 µF 0.1 µF 0.1 µF 0.1 µF 0.1 µF 0.1 µF	Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor	805	X7R or better	C0805X7R500104KNE	13	Venkel
C14 C20 C5	10 µF 10 µF 10 uF	Capacitor Capacitor Capacitor	B	Tantalum, 10 V	TA010TCM106MBN	3	Venkel
C8	See Table 2	Capacitor	805	NPO/COG		1	Venkel
U1	I.C.	Nand Gate	SO14		74ACTQ00	1	National
U2	Fiber-Optic	Transmitter		See Table 2	HFBR-1XXX	1	Agilent
U3	Fiber-Optic	Receiver		See Table 2	HFBR-2XXX	1	Agilent
U4	MC10H116FN	IC,ECL line rec.	PLCC20		MC10H116FN	1	Motorola
U5	TL431CD	IC, Voltage Reg.	SO-8		TL431CD	1	T.I.
L1	CB70-1812	Inductor	1812		HF30ACB453215	1	TDK
R12 R13	4.7 4.7	Resistor Resistor	805	5%	CR080510W4R7JT	2	Venkel
R20	12	Resistor	805	5%	CR080510W120JT	1	Venkel
R10	See Table 2	Resistor	805	5%		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%	CR080510W620JT	1	Venkel
R8 R9	See Table 2 See Table 2	Resistor Resistor	805	1%		2	Venkel
R6 R7	91 91	Resistor Resistor	805	5%	CR080510W910JT	2	Venkel
R11	See Table 2	Resistor	805	1%		1	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
Q3	MMBT3904LT1	Transistor	SOT-23		MMBT3904LT1	1	Motorola
J1		Pins			343B	9	McKenzie

Table 6. Parts List for the Transceiver in Figure 7

Designator	Part Type	Description	Footprint	Material	Part Number	Quantity	Vendor 1
C1 C4 C7	0.001 µF 0.001 µF 0.001 µF	Capacitor	805	NPO/COG	C0805NPO500102JNE	3	Venkel
C2 C3 C6 C9 C10 C14 C19	0.1 µF 0.1 µF 0.1 µF 0.1 µF 0.1 µF 0.1 µF 0.1 µF	Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor Capacitor	805	X7R or better	C0805X7R500104KNE	7	Venkel
C5 C20	10 µF 10 µF	Capacitor Capacitor	B	Tantalum, 10 V	TA010TCM106MBN	2	Venkel
C8	See Table 2	Capacitor	805	NPO/COG		1	Venkel
C11 C12	0.01 µF 0.01 µF	Capacitor Capacitor	805	X7R or better	C0805X7R500103JNE	2	Venkel
C13	2,000 pF	Capacitor	805	NPO/COG	C0805NP0500202JNE	1	Venkel
D1	HLMP-4700	LED lamp			HLMP-4700	1	Agilent
U1	I.C.	Nand Gate	SO14		74ACTQ00	1	National
U2	Fiber-Optic	Transmitter		See Table 2	HFBR-1XXX	1	Agilent
U3	Fiber-Optic	Receiver		See Table 2	HFBR-2XXX	1	Agilent
U4	ML6622	IC, quantizer	SO16		ML6622CS	1	MicroLinear
L1	CB70-1812	Inductor	1812		HF30ACB453215	1	TDK
R12 R13	4.7 4.7	Resistor Resistor	805	5%	CR080510W4R7JT	2	Venkel
R10	See Table 2	Resistor	805	5%		1	Venkel
R5	22	Resistor	805	5%	CR080510W220JT	1	Venkel
R8 R9	See Table 2 See Table 2	Resistor Resistor	805	1%		2	Venkel
R6 R7	91 91	Resistor Resistor	805	5%	CR080510W910JT	2	Venkel
R11	See Table 2	Resistor	805	1%		1	Venkel
R14 R17 R18	1 k 1 k 1 k	Resistor Resistor Resistor	805	5%	CR080510W102JT	3	Venkel
Q1 Q2	BFT92 BFT92	Transistor Transistor	SOT-23		BFT92	2	Philips
Q3	MMBT3904LT1	Transistor	SOT-23		MMBT3904LT1	1	Motorola
J1		Pins			343B	9	McKenzie

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