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An Experimental Optical-Fiber Link for Low-Bit-Rate Applications

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The design, construction, and performance of a practical optical link with interface circuits for coding and decoding 1.5-Mb/s, bipolar, digital signals are described. The optical devices used are light-emitting diodes and PIN photodiodes. A feedback or "transimpedance" preamplifier that incorporates a silicon junction-field-effect transistor is used in the receiver, which has a sensitivity of −57.2 dBm average optical power for a 10^{-9} bit-error-rate. The receiver demonstrates an optical power dynamic range of about 28 dB without requiring automatic gain control. Timing recovery is accomplished by a simple, conventional technique.

I. INTRODUCTION

Experimental repeaters for regenerating digital signals from a few Mb/s to a few hundred Mb/s for optical-fiber transmission have been reported.[1–7] In this paper, we report the results of an experiment in which a practical optical repeater of simple design and high performance with interface circuits for coding and decoding 1.5-Mb/s bipolar signals was constructed and evaluated. Such a low bit rate, bipolar, digital format (DS1) is presently used in telephone systems for the transmission of multiplexed, digitally encoded voice signals over copper twisted pairs. The optical system was designed to be transparent to the bipolar format of these electrical signals. It utilizes a directly modulated light-emitting-diode (LED) source and a PIN photodiode, incorporates a simple timing recovery circuit, and demonstrates receiver sensitivity that approaches theory.

The bipolar format consists of "zeros" and 50-percent duty cycle alternating positive and negatives "ones"; it, therefore, has three levels with a zero dc component. A straightforward scheme to translate the bipolar format to a unipolar format without increasing the bit rate might involve simple full-wave rectification. However, this is unacceptable in practice because violation of the bipolar format is used in system maintenance functions as an indication of system performance.

If the bipolar signal is transmitted as a three-level optical signal rather than a binary signal at the bipolar bit rate, 3 dB more average optical power would be required at the receiver detector for a given error-rate (assuming a thermal-noise dominated receiver). Implementing the three-level system would be more difficult, due to the nonlinearity of the LED. The three-level system also requires separate regenerators in the receiver for +1 and −1 pulse regeneration. If the bipolar signal is coded in a two-bit-for-one-bit manner (twice the bit rate), the receiver sensitivity would suffer a degradation of about 4.5 dB (PIN photodiode with FET amplifier input device)[8] compared to a binary format system at the bipolar bit rate. Although this system is about 1.5 dB less sensitive than the three-level system, repeater circuitry is simplified since the effects of LED nonlinearity are not important and only one pulse regenerator is required.

More efficient coding schemes are possible (e.g., 3-bit for 2-bit)[9] that allow the bipolar information to be transmitted at less than twice the information bit rate; however, the circuitry required to implement these schemes is substantially more complicated.

The simple coding format[9,10] used in our experiment is shown in Fig. 1. A positive one is coded into two consecutive 3-Mb/s ones (non-return-to-zero in this case) within a coding frame, a zero is coded as a one followed by a zero within a coding frame (this assignment is arbitrary; it could be 0, 1, instead), and a −1 is coded as two consecutive zeros. This coding format maintains desirable features of the bipolar signal, such as dc balance and substantial redundancy for error correction or monitoring. In addition, the code allows a receiver that is ac-coupled to have a constant threshold level at zero volts for a large range in received power level without automatic gain control. The pulse-transition density of the coded signal is very high, thus allowing a timing-recovery circuit in the receiver that is less critical than those encountered in more conventional binary systems.

The optical system is designed around an LED light source and a PIN photodiode. These devices are expected to be less expensive and require less control circuitry than lasers or avalanche detectors.

II. DESCRIPTION

A unidirectional optical-fiber link is shown in Fig. 2. The coder-transmitter converts the 1.5-Mb/s incoming bipolar signal into a 3-Mb/s unipolar optical signal for transmission via optical fibers. At the receiving terminal, the optical signal is regenerated and decoded back to the 1.5-Mb/s bipolar format. Depending upon the distance between terminals, one or more line repeaters may be needed. A line repeater might

CODING TABLE		
BIPOLAR	ENCODED	UNIPOLAR
	τ_1	τ_2
+1	1	1
0	1	0
-1	0	0

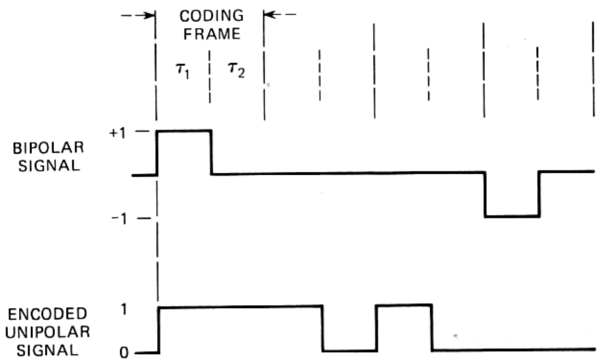

Fig. 1—Coding format.

include the receiver and driver shown in Fig. 2. and a simple regenerator since there is no need to decode or encode the unipolar signal.

2.1 Coder-transmitter

The circuits between the incoming electrical bipolar signal and the optical fiber consist of a bipolar-to-unipolar converter, a driver for the LED, and the LED. The bipolar signal is coupled to the converter by a transformer with a center-tapped secondary. Each half of the secondary is half-wave rectified; one rectifier generates a pulse when a "plus-one" appears at the input and the other generates a pulse when a "minus-one" appears at the input.

These outputs are then encoded into the 3-Mb/s format by TTL circuitry realized in two dual-in-line packages. The encoding process requires a clock signal, which is obtained from a timing-recovery circuit similar to that used in conventional digital repeaters.[11]

The digital output voltage of the converter is converted into 220-mA peak current pulses, which directly modulate the Burrus-type, diffused junction LED. A non-return-to-zero format is used since these LEDs are basically peak-power limited and the tolerable repeater span increases with average power when fiber-delay distortion is negligible.[8] The bandwidth of these devices is more than adequate for this bit rate.

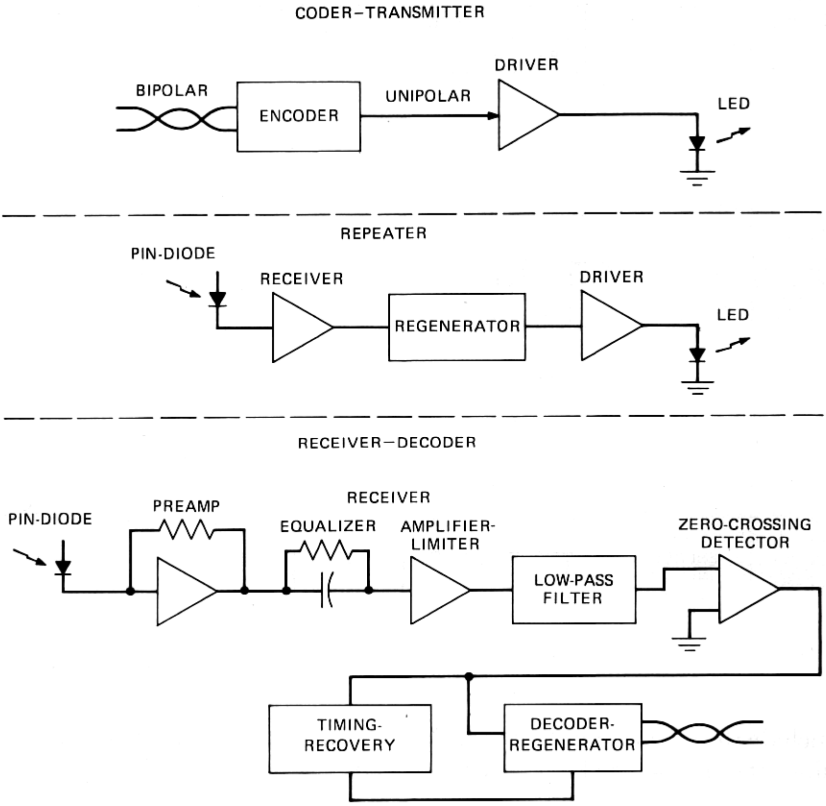

Fig. 2—Electronics of the optical-fiber link.

2.2 Receiver-decoder

The receiver and decoder-regenerator converts the unipolar signal on the optical fiber to a bipolar electrical signal. The input fiber is coupled to a PIN photodiode, which converts the optical pulses to electrical pulses which are then amplified sufficiently to be processed. The sensitivity of the receiver is determined by the thermal and shot noise generated in the "front-end" amplifier and the quantum efficiency and shot noise of the PIN photodiode. It has been shown that the total noise of the amplifier and diode may be referred to the input of the amplifier as a shunt current generator.[12] In the receiver described, the dominant source of noise is the silicon junction-field-effect transistor (Si JFET) input device since the leakage-current shot noise for most PIN photodiodes with active-area diameters less than 1.25 mm is small enough to be neglected. The mean-square current of the effective input noise current generator has been shown to be[12]

$$n_t = 4kTf_b \left[\left(\frac{1}{R_r} + \frac{\Gamma}{g_m R_r{}^2} \right) I_0 + \frac{(2\pi f_b C_T)^2 \Gamma}{g_m} I_2 \right],$$

where

k = Boltzmann's constant
T = absolute temperature
f_b = bit rate = 3 MHz
g_m = transconductance of the FET $\approx$ 5 mA/V
$C_T = C_{\text{diode}} + C_{\text{stray}} + C_{in\ \text{FET}} \cong$ 8 pF
R_r = parallel equivalent resistance at the input to the FET (diode bias return, FET bias, etc.)
$\Gamma \approx 0.7$ for typical Si JFETs.

The parameters I_0 and I_2 are weighting factors, which are determined by optical input and amplifier output pulse shapes;[12] in this case the input pulse is NRZ and rectangular and the output pulse NRZ and raised cosine; therefore,

$$I_0 = 0.55$$

$$I_2 = 0.085.$$

If the amplifier input device is an FET, it is possible to choose a value for R_r, such that the term associated with I_0 is negligible compared to the term associated with I_2, in which case an FET should be chosen to maximize $\sqrt{g_m}/C_T$.

The above analysis is for a non-feedback amplifier, which has an input time constant much larger than the signal period, $1/f_b$. In the present work, a "transimpedance" or feedback amplifier is used. Here, the output voltage is

$$e_o = -I_s Z_f \left(\frac{A\beta}{A\beta + 1} \right),$$

where

I_s = photodiode signal current
Z_f = feedback impedance = $1/(1/R_f + j\omega C_f)$
C_f = total shunting capacitance across R_f
R_f = feedback resistance
A = open-loop amplifier voltage gain
$\beta = Z_{in}/(Z_{in} + Z_f)$
Z_{in} = total impedance at the input of the open-loop amplifier

It can be shown that the feedback resistor R_f plays the same role as R_r in relation to noise.

Since, in this case, C_f is about $(1/80)C_t$, the time constant R_fC_f is 1/80 that of R_rC_t in the non-feedback design, and the signal is integrated over far fewer signal periods. There must be sufficient linear gain before pulse shape restoration, so that the amplifier following equalization does not affect the signal-to-noise ratio. In the case of the non-feedback amplifier, the integrated peak output voltage excursion may be many times that for a single pulse, in which case the optical power dynamic range of the amplifier is limited. The transimpedance amplifier, on the other hand, does not experience this problem, thus allowing a substantially greater dynamic range.

Following the pulse equalizer, the signal is further amplified by an amplifier that is linear at very low input power levels but acts as a symmetrical limiter at higher received optical power levels without degrading the performance. This feature eliminates the need for an automatic gain control.

The signal is bandlimited by a third-order Butterworth filter to reduce high-frequency, out-of-band noise, and then threshold detected by a zero-crossing detector.

Due to the coding format, the dc component of the received electrical signal voltage is always one-half the peak, thus the proper threshold level at the threshold detector is always zero when ac coupling is used at the input of the threshold detector.

The signal at the output of the zero-crossing detector, which has been quantized into two discrete voltage levels, has timing-jitter due to the presence of noise. This jitter is removed, as shown in Fig. 3, by sampling the signal at times which are determined by a 1.5-MHz, low-noise clock signal, which is recovered from the received signal by a high-Q, parallel-resonant circuit. This circuit is sustained in oscillation by 3.3-microsecond pulses, which are generated by a monostable multivibrator whenever a zero-one transition occurs in the received signal (Fig. 3, waveforms A-C). Since a zero-one sequence in the encoded signal only occurs at the beginning of a coding frame, the clock is synchronized with the frames. The 3-Mb/s received signal is demultiplexed into two 1.5-Mb/s signals by two sample and store circuits, one of which samples the first bit in a coding frame on positive-going clock transistions (Fig. 3, waveform D), and the other samples the second bit in a frame on negative-going clock transistions (Fig. 3, waveform E). These two 1.5-Mb/s signals are then reconstituted into the original DS1 (1.5-Mb/s, 50-percent duty-cycle, bipolar) signal by comparing the states of the two demultiplexed signals at the end of each coding frame (Fig. 3, waveform F). Pulse regeneration and decoding to bipolar is accomplished with TTL circuits

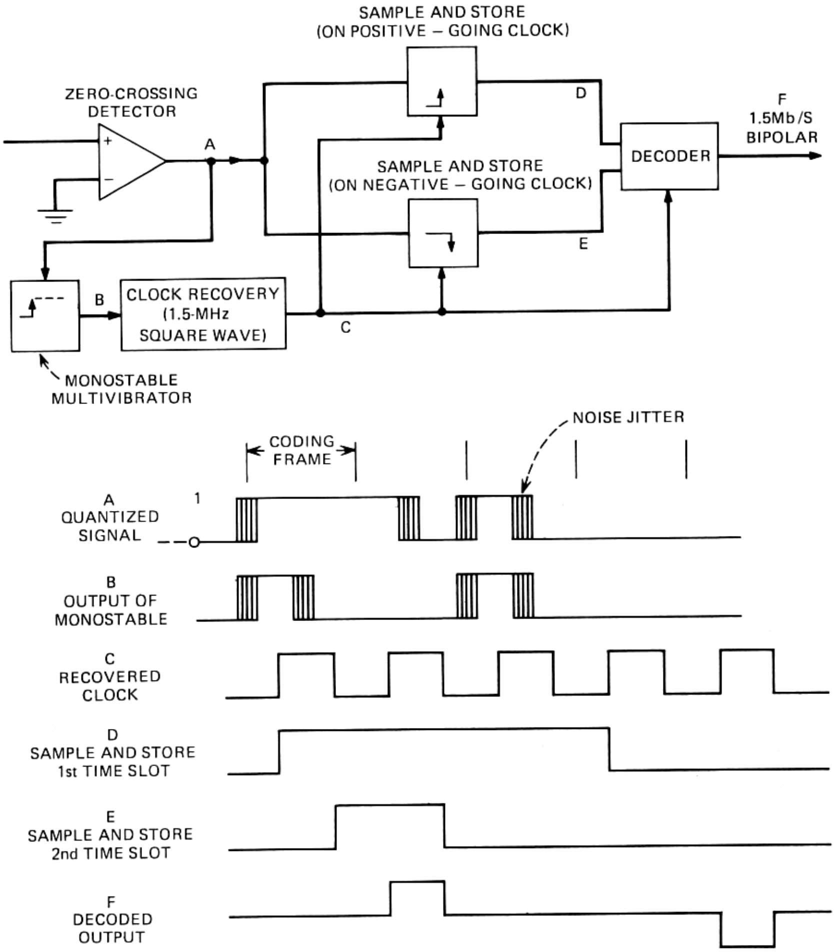

Fig. 3—Decoding process.

consisting of 3 D-type flip-flops, 3-2 input NAND gates, and an inverter. The output of the decoder is coupled to a twisted pair line.

III. SYSTEM PERFORMANCE

3.1 Evaluation procedure

To evaluate the system error performance, dynamic range, and timing jitter, the coder-transmitter and the receiver-decoder were physically separated and optically coupled through an air path into which the required amount of attenuation was placed. The two sections were then packaged in a plug-in module of dimensions, $1\frac{5}{6}$ inches × $8\frac{1}{2}$ inches ×

9 inches, and optically coupled via an optical-fiber path into which a controlled amount of attenuation was placed. No degradation in performance was observed.

3.2 Error performance

The theoretical average optical power required for a given error probability is[12]

$$P = \frac{h\nu}{\eta e} Q n_t^{1/2},$$

where

P = average optical power required to produce an error probability of P_e
h = Planck's constant
ν = optical frequency
η = photodiode quantum efficiency
e = electron charge
$Q = \sqrt{2}\, erfc^{-1}(2P_e)$
P_e = probability of error.

The photodiode used in the error probability measurements had a quantum efficiency of about 65 percent.

The theoretical and experimental error probability curves are presented in Fig. 4. The 0.5-dB discrepancy is due to noise contributions of amplifier stages following the FET input stage and measurement errors. The data point at the 1.4×10^{-9} rate was obtained by counting the errors that occurred in 12 time periods of 10^9 time slots each (≈5 min.). During one of these periods, a burst of 30 errors occurred due to electromagnetic interference and the data obtained during this period were omitted.

The curves in Fig. 4 indicate the error probability at the coded 3-Mb/s rate, the error probability at the 1.5-Mb/s rate would be about a factor of two higher (some error correction takes place in the decoder); however, this increase could be compensated for with about a 0.2 dB increase in optical power.

3.3 Dynamic range

Optical power dynamic range is described as

$$P_d(\text{dB}) = P_{max}(\text{dB}) - P_{min}(\text{dB}),$$

where

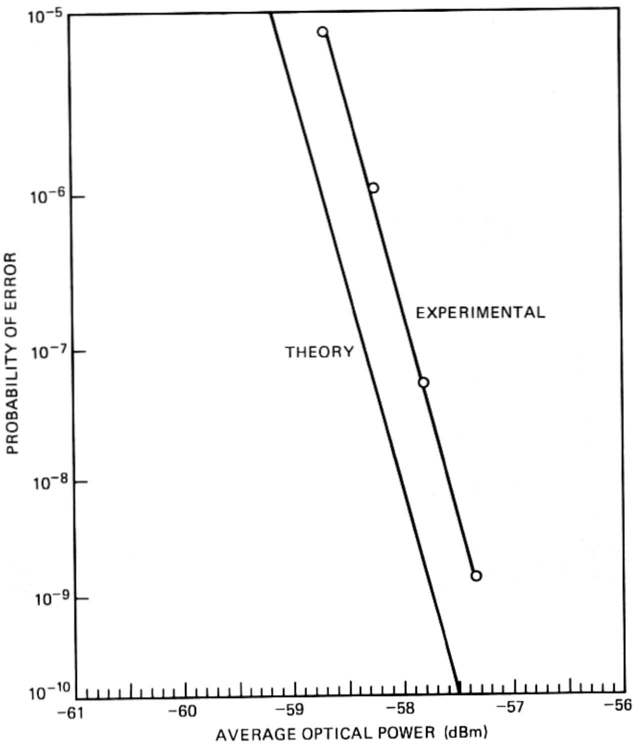

Fig. 4—Experimental and theoretical error vs. received average optical power.

P_{max} = maximum received optical power level before nonlinear effects degrade performance.

P_{min} = optical power required to maintain a 10^{-9} error probability.

The optical power dynamic range for the receiver described here is about 28 dB.

3.4 Timing jitter

The phase jitter in the decoded pulse stream was observed to be about 10 degrees RMS at a received optical power level of about −57.8 dBm.

3.5 Waveforms

The oscilloscope pictures in Fig. 5(a–e) show waveforms at several points in the system at various input power levels. The "eye diagram" in Fig. 5(a) is taken at the output of the "front-end" amplifier and illustrates the signal integration due to the capacitance across the feedback resistor. Fig. 5(b) and (c) were taken at the input to the filter, Fig. 5(b)

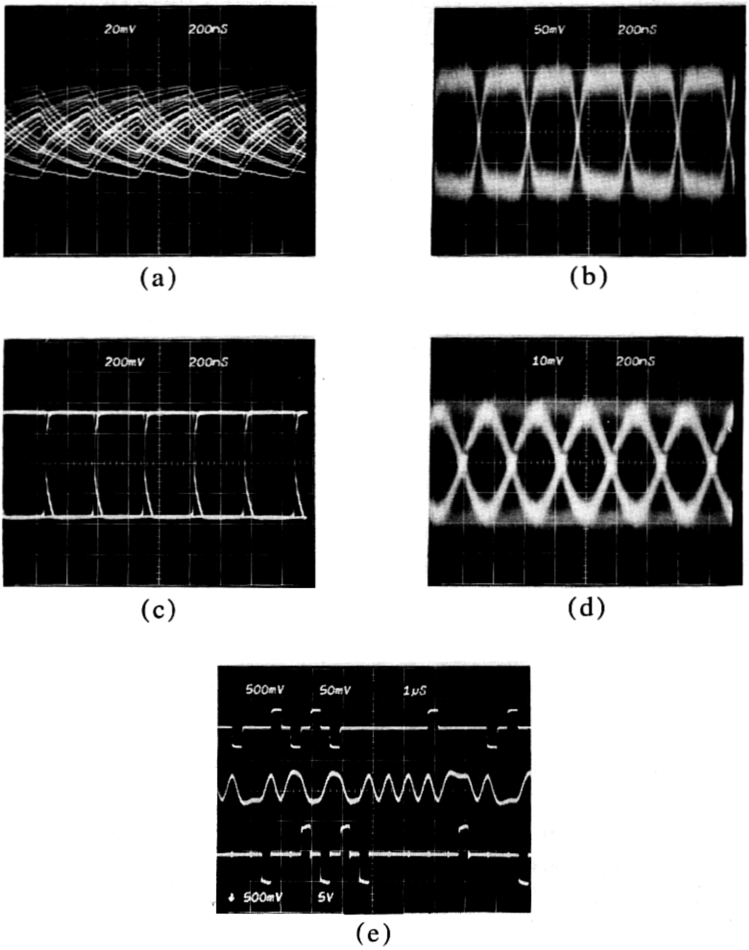

Fig. 5—Receiver waveforms (voltages: 0.1 × actual value)

was taken at a received optical power level of −47 dBm, and Fig. 5(c) was taken at an optical power level of −28 dBm when the second amplifier acts as a limiter.

Figure 5(d) demonstrates the "eye," after filtering, at a −57.2 dBm optical power level. The waveforms from top to bottom in Fig. 5(e) are: the bipolar signal at the input to the coder-transmitter, the 3-Mb/s received signal at the output of the filter, and the regenerated and decoded bipolar signal.

Power consumption

Total power consumption for the transmitter and receiver was about 1.75 watts.

IV. SUMMARY

A practical optical-fiber link of simple design for faithful transmission of 1.5-Mb/s bipolar, digital signals has been built and tested. High performance is achieved through the use of a transimpedance preamplifier that affords receiver sensitivity that approaches the theoretical limits imposed by commercially available silicon junction-field-effect transistors.

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