4-Gb/s PSK Homodyne Transmission System Using Phase-Locked Semiconductor Lasers

J. M. KAHN, A. H. GNAUCK, J. J. VESELKA, S. K. KOROTKY, SENIOR MEMBER, IEEE, AND B. L. KASPER, MEMBER, IEEE

Abstract—**We have achieved homodyne detection of 4-Gb/s pilot-carrier BPSK optical signals using external-cavity semiconductor lasers synchronized by a linear phase-locked loop. A $2^{15} - 1$ PRBS has been transmitted through a short fiber with a receiver sensitivity of −44.2 dBm or 72 photons/bit. After transmission through 167 km of standard single-mode fiber, the sensitivity is −43.6 dBm or 83 photons/bit. We have employed a balanced PIN/HEMT transimpedance receiver which has a 3-dB bandwidth from 100 kHz to 10.1 GHz and an average equivalent input noise current of 10.8 pA/$\sqrt{\text{Hz}}$.**

INTRODUCTION

AMONG techniques for coherent detection of optical signals, homodyne offers the advantages of high channel packing density, minimum required receiver bandwidth, reduced receiver thermal noise, and linear demodulation. Homodyne detection of phase-shift-keyed (PSK) signals yields, in theory, the highest sensitivity of any binary signaling technique employing single-bit decisions. In the wavelength range of interest for high-speed lightwave transmission, linear optical phase-locked loops (OPLL's) have been employed for homodyne detection of pilot-carrier binary phase-shift-keyed (BPSK) signals with 1.52-μm HeNe lasers at 140 Mb/s [1, 2] and 700 Mb/s [2], and with 1.51-μm external-cavity semiconductor lasers (ECL's) at 1 Gb/s [3] and 2 Gb/s [4]. In addition, a nonlinear Costas OPLL with 1.32-μm YAG lasers has been used to detect suppressed-carrier BPSK [2]. We report here an experimental pilot-carrier BPSK homodyne system that has allowed detection of 4-Gb/s data with record sensitivity. We also describe a 10-GHz balanced PIN/HEMT transimpedance receiver than has been used in the experiment.

SYSTEM CONFIGURATION

The overall design of our system (Fig. 1) is similar to that employed in experiments at 1 Gb/s [3] and 2 Gb/s [4]. The transmitter and local-oscillator (LO) sources are 1.508-μm InGaAsP ECL's [5] which have a beat linewidth of 2.5 kHz. The LO laser is fitted with a two-electrode chip, so that the FM response has constant magnitude and phase from dc to at least 10 MHz. The transmitter and LO are protected from reflective feedback using Faraday isolators. For the *Z*-cut, traveling-wave LiNbO_3 phase modulator, Fig. 2 indicates the RF power in the 50-Ω drive line required to produce a π peak-to-peak phase shift. The required drive increases about 2.5 dB over the frequency range used for 4-Gb/s NRZ modulation, so we insert an equalizer in the 50–Ω line prior to the drive amplifier. The modulator optical insertion loss is 3.6 dB. For transmission of a BPSK signal, the modulation angle is adjusted to ±75°, leaving a pilot carrier containing 6% of the −1.9 dBm launched optical power. Signals are transmitted through either 5 m or 167 km of standard signal-mode fiber (SMF), the latter having a loss of 40.5 dB and an estimated dispersion of 2.3 ns/nm.

The combined signal and LO radiation illuminates a balanced receiver which, like a previous design [6], contains separate amplifiers for the data signal and the phase-error signal required for the OPLL. A simplified schematic of the receiver is shown in Fig. 3. *PD*1 and *PD*2 are 25-μm-diameter, back-illuminated, planar InGaAs p-i-n photodiodes having 80% quantum efficiency. The wideband, hybrid front end is of a transimpedance design, and includes three-stage, HEMT-based inverting amplifier *A*4 with negative feedback through resistor *R*8 (330 Ω). The total input capacitance is 0.47 pF, including 0.19 pF from the gate-source capacitance of the input HEMT, and 0.08 pF from each of *PD*1 and *PD*2. Bond-wire inductances *L*1–*L*3 provide peaking for widened frequency response and reduced noise. The swept-frequency response and equivalent input noise current of the wideband receiver front end are shown in Fig. 4. The differential response exhibits a 3-dB bandwidth from 100 kHz to 10.1 GHz. Over this bandwidth, the common-mode rejection ratio is at least 24 dB, and the average equivalent input noise current is 10.8 pA/$\sqrt{\text{Hz}}$. In the present homodyne transmission experiment, the detected LO photocurrent is 1.3 mA.

Returning to Fig. 3, the receiver contains additional circuitry to form a dc-coupled phase detector with low 1/f noise [6]. Resistors *R*6 and *R*7 (2 kΩ) sense the currents in photodiodes *PD*1 and *PD*2, and the resulting voltages are buffered in *A*2 and *A*3, and summed in *A*1 (all three are high-speed, JFET-input operational amplifiers). Resistors *R*4 and *R*5 (100 Ω) prevent microwave resonances in the wideband front end that might be caused by connecting leads off the hybrid microcircuit to the operational amplifiers. The phase detector differential response has a pole at 2.5 MHz because of the time constant formed by resistor *R*6 and the parallel combination of bypass capacitor *C*1 (10 pF) and the input capacitance of *A*2 (likewise for *R*7, *C*2, and *A*3). The phase detector has an equivalent input noise current of 8.1 pA/$\sqrt{\text{Hz}}$. The back-reflection from each photodiode into the fiber is

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J. M. Kahn and A. H. Gnauck are with AT&T Bell Laboratories, Crawford Hill Laboratory, Holmdel, NJ 07733.

J. J. Veselka and S. K. Korotky are with AT&T Bell Laboratories, Crawfords Corner Road, Holmdel, NJ 07733.

B. L. Kasper is with AT&T Bell Laboratories Solid State Technology Center, Breinigsvelle, PA 18031.

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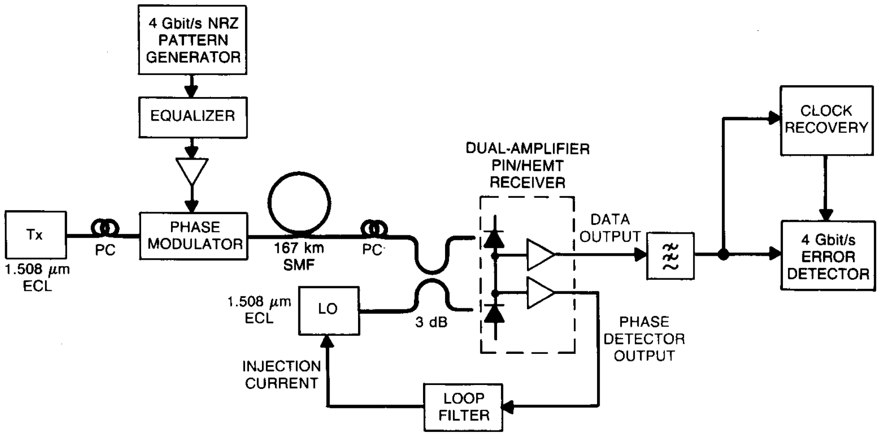

Fig. 1. Diagram of the experimental 4 Gb/s PSK homodyne system.

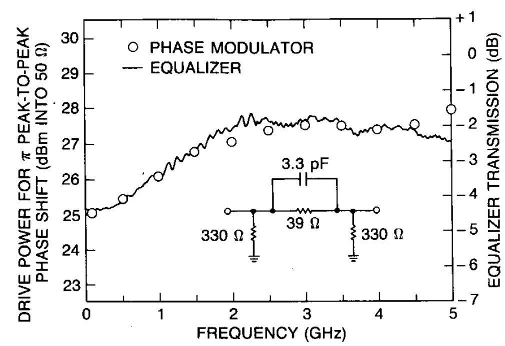

Fig. 2. Measured frequency response of Z-cut, traveling-wave LiNbO$_3$ phase modulator and equalizer for its drive signal. Inset: schematic of the equalizer.

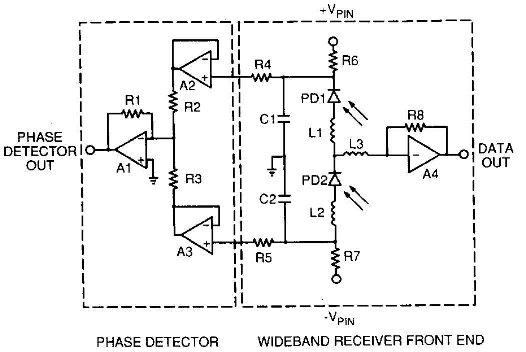

Fig. 3. Simplified schematic of balanced p-i-n receiver incorporating HEMT-based transimpedance amplifier for data signal, in addition to dc-coupled circuitry for phase-error signal.

about −60 dB. This ensures that reflected LO radiation that is subsequently Rayleigh-scattered from the transmission fiber will not induce a large OPLL phase error, and minimizes drift of the phase detector dc balance [7]. In the present experiment, the drift is equivalent to ±1.5° in 5 min.

Output of the phase detector is processed by a proportional-integral loop filter, and the correction signal is resistively added with the dc current to the low-biased electrode of the LO

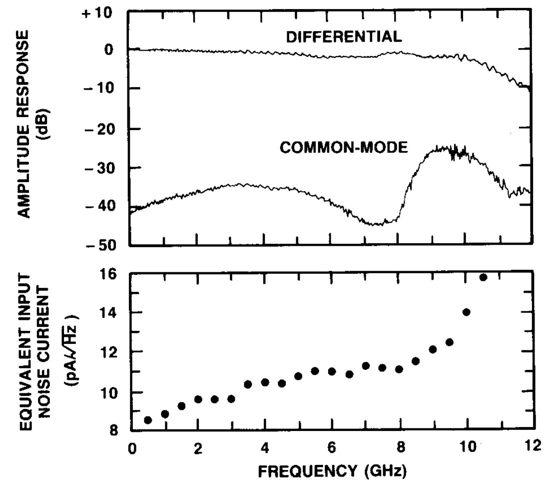

Fig. 4. Measured amplitude response and equivalent input noise current of PIN/HEMT transimpedance receiver for data signal.

laser. This forms a second-order OPLL [8] with natural frequency $\omega_n = 600$ krad/s, damping coefficient $\zeta = 0.71$, and dc loop gain $K_v = 4.3 \times 10^9 s^{-1}$. The wideband receiver front end directly yields the data signal, which is amplified and then passed through a three-pole Chebyshev low-pass filter having a 3-dB bandwidth of 3100 MHz. An electronic phase-locked loop is employed for clock recovery.

System Performance

The bit-error-rate performance of our system is shown in Fig. 5. With 5 m of SMF and a $2^{15} - 1$ PRBS, the receiver sensitivity is −44.2 dBm or 72 photons/bit. After transmission through 167 km of SMF, information-limited chromatic dispersion degrades the sensitivity by 0.6 dB, to −43.6 dBm or 83 photons/bit. Compared to the quantum limit of 9 photons/bit or −53.2 dBm, our result in the absence of dispersion is 9.0 dB worse. A penalty of 1.0 dB results from incomplete suppression of the thermal noise of the receiver data preamplifier. Photodiode quantum efficiency and excess loss of the 3-dB coupler cause a 1.1-dB penalty, and pilot-

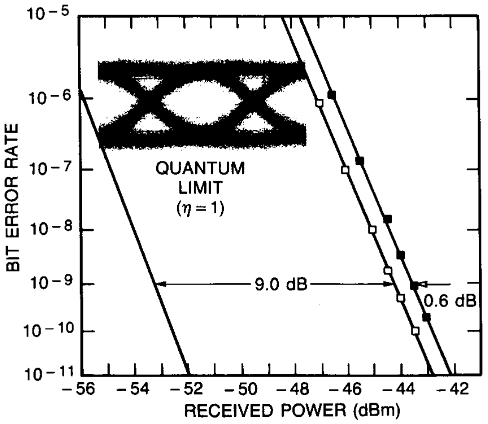

Fig. 5. Bit-error rate versus received power for 4 Gb/s, $2^{15} - 1$ PRBS transmitted through standard single-mode fiber: (□) 5 m; (■) 167 km. Inset: eye pattern after 167 km transmission at −44 dBm received power.

carrier transmission represents a penalty of 0.3 dB. OPLL phase error from laser phase noise causes approximately a 0.5-dB penalty, and a penalty of about 0.5 dB results from the OPLL phase error induced by the data-to-phase-lock crosstalk [9], [3]. A penalty of approximately 0.5 dB results from the use of third-order post-detection filter instead of the idealized matched filter; an additional 0.8-dB penalty arises from the need to employ a wider-than-optimum filter because of the imperfect frequency response of the PSK transmitter. The remaining penalty is 4.3 dB, and at least 2.8 dB of this is caused by intersymbol interference, due to the nonideal frequency response of the PSK transmitter and linear-channel amplifiers.

Our result with a short fiber represents a 6.3-dB improvement over the best previous baseline sensitivity at this bit rate, i.e., 309 photons/bit, attained using asynchronous heterodyne detection of CPFSK [10]. Unlike the present experiment, the heterodyne technique permitted cancellation of fiber chromatic dispersion through equalization of the intermediate-frequency signal, and was able to achieve penalty-free transmission through 202 km of SMF at a wavelength of 1.55 μm. In the present experiment, transmission distance is limited by the high fiber loss of 0.244 dB/km at the 1.508-μm wavelength. Retuning of the ECL's to 1.55 μm should allow transmission through approximately 200 km of SMF having a loss of 0.20 dB/km, assuming that the chromatic-dispersion penalty increases to about 1 dB [11].

CONCLUSION

In summary, we have achieved homodyne detection of 4-Gb/s pilot-carrier BPSK optical signals using external-cavity semiconductor lasers synchronized by a linear phase-locked loop. We have transmitted a $2^{15} - 1$ PRBS through a short fiber with a sensitivity of 72 photons/bit, and through 167 km of standard single-mode fiber with a sensitivity of 83 photons/bit.

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