1 Gbit/s PSK Homodyne Transmission System Using Phase-Locked Semiconductor Lasers

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Abstract—**We have demonstrated homodyne detection of 1 Gbit/s pilot-carrier BPSK optical signals using phase-locked 1.5 μm external-cavity semiconductor lasers. After 209 km fiber transmission of a $2^{15} - 1$ PRBS, the measured receiver sensitivity is -52.2 dBm or 46 photons/bit. We present experimental evidence of the data-to-phase-lock crosstalk that potentially limits the usable ratio of linewidth to bit rate in pilot-carrier PSK homodyne systems.**

Introduction

HOMODYNE detection of phase-shift-keyed (PSK) optical signals offers, in theory, the best sensitivity of any binary signaling technique employing single-bit decisions. Among so-called coherent techniques, homodyne also promises the advantages [1] of high channel packing density, minimum required receiver bandwidth, reduced receiver thermal noise, and freedom from nonlinear electronic signal processing. In the wavelength range of interest for high-speed lightwave transmission, HeNe lasers have been used to demonstrate a 140 Mbit/s pilot-carrier homodyne system [2], and external-cavity semiconductor lasers (ECL's) have been used to construct homodyne optical phase-lock loops (OPLL's) [3], [4], but there have been no reports of homodyne detection using semiconductor lasers. We describe here an experimental pilot-carrier PSK homodyne system using ECL's which has allowed detection of 1 Gbit/s data with record sensitivity [5].

The performance optimization of balanced, linear OPLL's for homodyne detection of pilot-carrier PSK signals has been analyzed by Kazovsky [6] and is reviewed briefly here. Design of an OPLL for operation with 10° rms phase error represents a good compromise between penalties for imperfect carrier phase recovery [7] and pilot-carrier transmission. The three most important sources of OPLL phase error generally are 1) the Lorentzian component of laser phase noise, 2) the shot noise of the local oscillator (LO), and 3) the data-to-phase-lock crosstalk. For small ratios of linewidth to bit rate, the effect 3) is approximately accounted for by treating the low-frequency data content as white noise. An optimized loop operates with 7° rms phase error from each of sources 1) and 3), and with negligible contribution from 2). For a second-order OPLL characterized by [8] natural frequency ω_n, damping constant $\zeta = 0.707$, and noise bandwidth $B_L = 0.530\omega_n$, tracking laser phase noise with 7° rms error requires $B_L = 78\Delta\upsilon_{\text{beat}}$, where $\Delta\upsilon_{\text{beat}}$ is the laser beat linewidth. The resulting value of B_L, in conjunction with the modulated signal power required to attain a specified bit error rate (BER), dictates the pilot-carrier power required so that the data-to-phase-lock crosstalk induces only a 7° rms phase error. Transmission of the pilot carrier represents a power penalty which limits the usable ratio of linewidth to bit rate to values below approximately 10^{-5}.

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System Configuration

Fig. 1 depicts our experimental homodyne system. The transmitter and LO sources are 1.508 μm InGaAsP ECL's [9] which have a beat linewidth of 3 kHz. Each ECL is contained in a Plexiglas box in a ± 1°C temperature-controlled environment. Previous measurements on these ECL's have demonstrated a relative frequency drift of <600 kHz in 5 min and a relative frequency jitter of <200 kHz pp. The latter consists primarily of frequency components below 4 kHz, and is estimated to induce about 1° rms phase error in the present OPLL. The ECL's contain two-electrode chips to allow fast frequency modulation and are protected from reflective feedback using Faraday isolators.

The fiber-pigtailed, X-cut, traveling-wave $LiNbO_3$ phase modulator requires 9 V to produce a 180° phase shift. The electrode frequency response drops 2 dB between dc and 1.5 GHz, and is compensated by a passive equalizer at the power amplifier input. For transmission of a BPSK signal, the modulation angle is adjusted to $\pm 69°$, leaving a pilot carrier containing 13 percent of the transmitted power. At the modulator output the launched optical power is -1 dBm.

Signals are transmitted through either 5 m or 209 km of spooled single-mode fiber, the latter having a loss of 50.7 dB and an estimated dispersion of 2.9 ns/nm. The combined signal and LO radiation illuminates a balanced p-i-n/FET receiver which contains two signal amplification paths [4]. An HEMT-based transimpedance circuit having a 3 dB bandwidth of 95 kHz to 3.2 GHz is provided for the coherently demodulated data. In addition, a JFET-based circuit extracts signals from sensor resistors placed in series with each p-i-n, forming a dc-to-2.1 MHz phase detector with low $1/f$ noise. The detected LO photocurrent of 1.1 mA gives rise to a combined shot- and thermal-noise power which is 6.2 dB above the thermal noise of the data preamplifier; for the phase detector the corresponding ratio is 16.4 dB. The receiver quantum efficiency is 91 percent, and its optical return loss is approximately 50 dB. This high return loss ensures that Rayleigh-scattered, reflected LO radiation will not dominate the phase error as it did in a previous OPLL [3].

The phase detector output is processed by a lag-lead

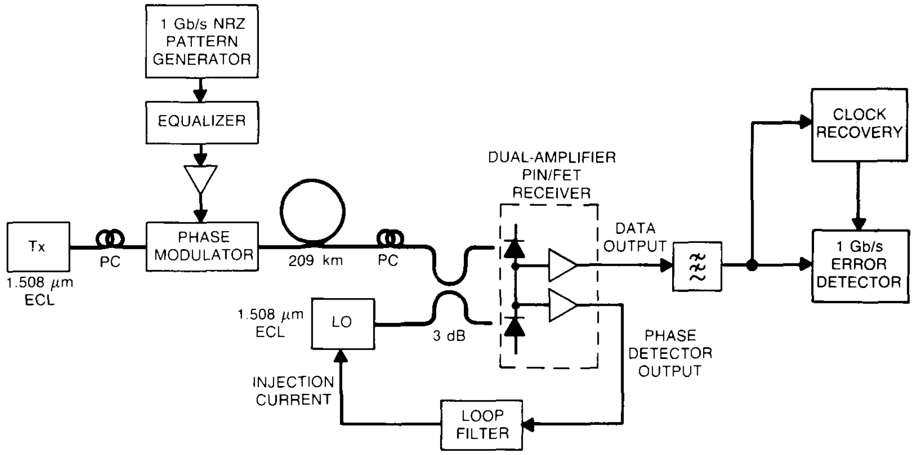

Fig. 1. Diagram of the experimental 1 Gbit/s PSK homodyne system.

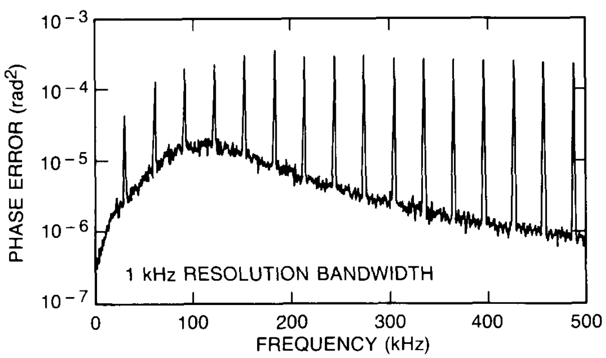

Fig. 2. Spectrum of the phase detector output signal in loop locked to a 1 Gbit/s, $2^{15} - 1$ pilot-carrier PSK signal. Modulation angle is $\pm 69°$ and loop parameters are $\omega_n = 700$ krad/s, $\zeta = 0.68$.

integrator [8] and the correction signal is resistively added with the dc current to the low-biased electrode of the LO laser. Output of the receiver data preamplifier directly yields the baseband data signal, which is filtered using a 700 MHz, three-pole Chebyshev filter. An electronic phase-lock loop is employed for clock recovery.

System Optimization and Performance

Optimization of system BER performance led to a choice of the OPLL parameters [8] $\omega_n = 600$ krad/s, $\zeta = 0.71$, and $B_L = 320$ kHz, and it determined the $\pm 69°$ modulation angle. The OPLL has dc loop gain $K_v = 5.5 \times 10^9\ \text{s}^{-1}$.

Fig. 2 shows the spectrum of the phase detector signal with the loop locked to a 1 Gbit/s pilot-carrier signal ($2^{15} - 1$ PRBS), and with OPLL parameters close to those listed above. The continuous distribution represents the density of phase error from the Lorentzian phase noise. Below a frequency breakpoint of order $\omega_n/2\pi$ (110 kHz) this density decreases with decreasing frequency, and above that breakpoint it is the tail of the Lorentzian distribution. Integration of the continuum yields a 6° rms phase error, in agreement with the value expected for the present beat linewidth and loop bandwidth [6], and taking into account the effect of the 130 ns loop propagation delay [10]. Also visible in Fig. 2 are discrete components of the data signal at multiples of 1 GHz/($2^{15} - 1$) = 30.5 kHz. Below the frequency breakpoint of $\omega_n/2\pi$ the components are reduced from their normally equal amplitudes, implying that at these discrete frequencies, compensating phase errors have been imparted to the recovered carrier. Precise empirical determination of the resulting phase error would require measurement of the closed-loop complex transfer function, which has not been done, but the error is evidently of the same order as the 4° rms predicted by theory [6].

The system impact of the data-to-phase-lock crosstalk can be understood with reference to Fig. 3, which shows the portion of a received 1 Gbit/s, $2^{15} - 1$ PRBS that is most strongly affected. With loop parameters near optimum [Fig. 3(a)] slight baseline wander is evident, and it becomes more severe upon doubling the loop natural frequency [Fig. 3(b)]. When we adjust OPLL parameters and modulation angle to optimize system performance with this pseudorandom pattern, we are essentially maximizing detection efficiency during the portion of the pattern that is illustrated in Fig. 3. In order for homodyne systems to operate with ratios of linewidth to bit rate that are higher than we employ here, it would be useful to line code the data to reduce the low-frequency content, or to utilize alternative OPLL designs [6], [1].

Fig. 4 illustrates the BER performance of our system. With 5 m of fiber, the receiver sensitivity is −52.8 dBm for a $2^{10} - 1$ PRBS and −52.3 dBm for a $2^{15} - 1$ PRBS. After 209 km fiber transmission of the $2^{15} - 1$ PRBS, the sensitivity is −52.2 dBm or 46 photons/bit. This latter sensitivity equals the best previously reported for a lightwave transmission experiment, i.e., 45 photons/bit at 400 Mbits/s obtained using heterodyne DPSK [11]. Our result represents effectively a 6.4 dB improvement over the best previous sensitivity at a similar bit rate, 200 photons/bit at 1.2 Gbits/s, also achieved with heterodyne DPSK [12]. The improvement exceeds substantially the 3.5 dB theoretical sensitivity advantage of the present technique over heterodyne DPSK, illustrating the importance of other advantages of homodyne for high-speed systems (see Introduction).

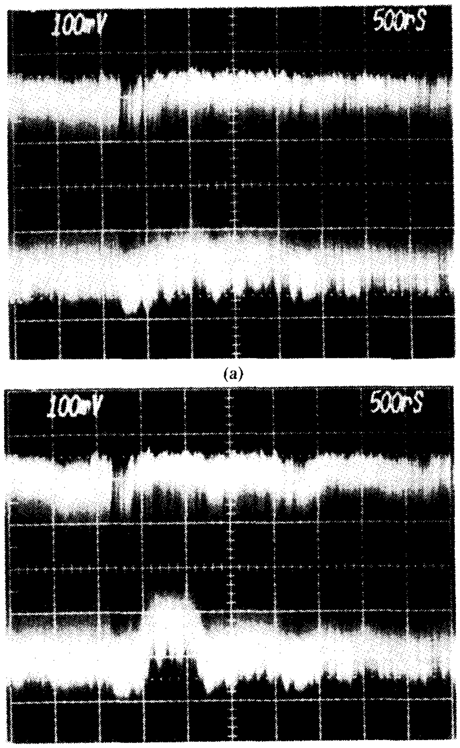

Fig. 3. Portion of received 1 Gbit/s, $2^{15} - 1$ PRBS. Modulation angle is $\pm 69°$ and loop parameters are (a) $\omega_n = 725$ krad/s, $\zeta = 0.73$; (b) $\omega_n = 1450$ krad/s, $\zeta = 1.46$.

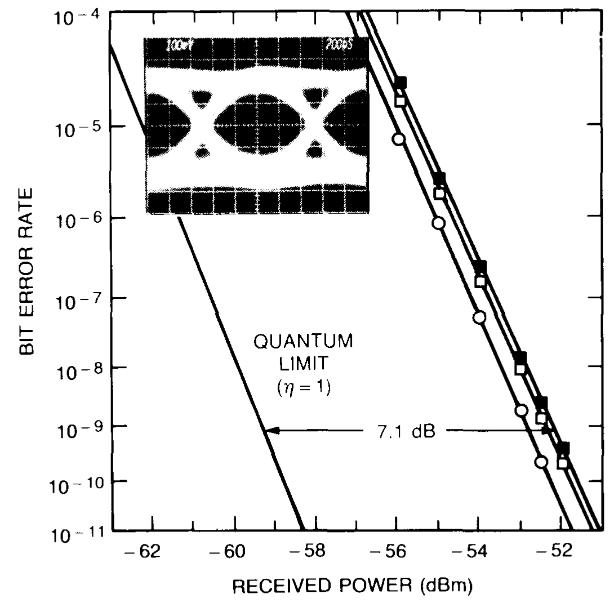

Fig. 4. Bit error rate versus received power; (○) $2^{10} - 1$, 5 m; (□) $2^{15} - 1$, 5 m; (■) $2^{15} - 1$, 209 km. Inset: eye diagram of received 1 Gbit/s, $2^{15} - 1$ PRBS with -52 dBm received power.

Compared to the quantum limit of 9 photons/bit or -59.3 dBm, our experimental sensitivity is 7.1 dB worse. A penalty of 1.2 dB results from incomplete suppression of thermal noise of the receiver data preamplifier. Receiver coupling losses cause a 0.6 dB penalty, and pilot-carrier transmission represents a 0.6 dB penalty. A penalty of approximately 0.8 dB results from our use of a third-order postdetection filter instead of the idealized matched filter. OPLL rms phase error from laser phase noise causes approximately a 0.5 dB penalty. We estimate a penalty of 1.5 dB from data-to-phase-lock crosstalk; the better sensitivity for a $2^{10} - 1$ PRBS results mainly from the reduced importance of this effect. The remaining penalty is 1.9 dB and it probably arises chiefly from imperfect frequency response of the phase modulator and receiver linear channel.

Conclusion

In summary, we have demonstrated homodyne detection of 1 Gbit/s pilot-carrier BPSK optical signals using external-cavity semiconductor lasers. We have transmitted a $2^{15} - 1$ PRBS through 209 km of fiber with a receiver sensitivity of 46 photons/bit.

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