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THE EFFECT OF SEMICONDUCTOR LASER DIODE INTENSITY FLUCTUATIONS ON OPTICAL COMMUNICATION SYSTEMS USING PPM SIGNALING

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ABSTRACT

The degradation in performance of a direct detection optical communication system using PPM signaling, due to semiconductor laser light intensity fluctuations is described.

INTRODUCTION

GaAs semiconductor laser diodes are attractive candidates for an optical transmitter in both free-space intersatellite optical communication links (GaAlAs diodes with = 800 nm) and in fiber optical transmission systems (InGaAsP diodes with = 1300 nm). Both types of systems are often based on an optical pulse position modulation signaling format in which a group of L binary source digits is transmitted every T seconds as a single light pulse of duration $\Delta\tau$ = T/2 seconds, located in one of $Q = 2^L$ possible time slots within the baud interval [0,T]. This format was first suggested by Pierce [1], and this type of direct detection optical communication system has been studied extensively [2]-[4]. However, all of these analyses have assumed the laser transmitter outputs a light pulse of fixed shape. The purpose of this short note is to show that fluctuations in the peak intensity of such light pulses can severly degrade the performance of an optical ppm system operated under even the most ideal conditions.

If no background radiation or other sources of noise are present at the receiver, the only source of error in this type of direct detection system arises from the failure of the photodetector to absorb one or more photons from the received light pulse. This occurs with probability $\exp(-\lambda_s\Delta\tau)$ where the received light pulse is assumed rectangular in shape and generates a peak photoabsorption rate of λ_s photons/second. $\lambda_s\Delta\tau$ is the average number of photons detected per light pulse. If no photons are absorbed from the one time slot within [0,T]that contained the light pulse, all L binary source digits are lost; otherwise all L bits are correctly received. Under these conditions, the system is said to operate in the quantum limited regieme.

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EFFECTS OF LASER INTENSITY FLUCTUATIONS

Non-ideal laser light that contains both intensity and phase fluctuations is often described phenomenologically as a superposition of an electric field of fixed amplitude and frequency but uniformly distributed phase and a narrow band Gaussian noise field [5]-[6]. This model leads to the following probability for the laser field having an intensity between I and I+dI

$$p(I)dI = \frac{1}{2\psi} \exp\left(-\frac{I+P^2}{2\psi}\right) I_0\left(\frac{\sqrt{IP^2}}{\psi}\right) dI \qquad (1)$$

Here I_0 is a modified Bessel function, p represents the amplitude of the coherent electric field and ψ is the variance of the Gaussian noise component. A recent experimental study of an InGaAsP laser diode revealed that (1) accurately models the intensity fluctuations of the laser light produced.

Since it is well known that the photon absorption process is conditionally Poisson [8]-[9], the effect of laser light characterised by (1) on the performance of a direct detection optical ppm system are easily computed. In the ideal case of quantum limited operation, the received symbol error probability is given by

$$P_e = E\{e^{-\lambda_s \Delta\tau}\} \qquad (2)$$

where the expectation is over the quantity λ_s , and λ_s is related to the received optical field intensity I as $\lambda_s = \eta\, I/hf$, η being the quantum efficiency of the photodetector. straightforward transformation of the probability law (1) leads to the closed form evaluation [10] of (2) as

$$P_e = \frac{2\psi' + 1}{1 + 2\psi'(1 + \langle n_s \rangle)} \exp\left[\frac{-\langle n_s \rangle}{1 + 2\psi'(1 + \langle n_s \rangle)}\right] \qquad (3)$$

In (3) , $\langle n_s \rangle$ represents the average number of detected photons in a received light pulse and ψ' is the dimensionless quantity ψ/p^2 . $\psi' = 0$ corresponds to the ideal case in which the diode laser light has no intensity fluctuations and (3) reduces to the quantum limited case.

Figure 1 plots the symbol error probability p_e as a function of ψ' for the two cases $\langle n_s \rangle = 10$ and $\langle n_s \rangle = 20$ under quantum limited operation (i.e. the photodetector rigisters photocounts directly, has no noise of it`s own, and no background radiation is present). Figure 1 is valid for any alphabet size Q system, as it depends only on the average number of detected photons per ppm symbol (light pulse).

Since there are no ideal photon detectors available at the wavelengths of interest, it is much more realistic to compute the performance of the ppm system when an avalanche photodetector (APD) is used to detect the received light pulse. Under these circumstances, the receiver must determine in which of the Q possible time slots the largest value of the APD output occured. The number of electrons generated by the APD output current across the load resistor of size R_L due to the received light pulse is reasonably accurately described [2] as a Gaussian random variable whose mean and variance are given by [4]

$$\bar{n} = G[\lambda_s \Delta\tau + \lambda_0 \Delta\tau + \frac{i_b}{q} \Delta\tau] + \frac{i_s}{q} \Delta\tau \tag{4}$$

$$\mathrm{var}_n = G^2 F[\lambda_s \Delta\tau + \lambda_0 \Delta\tau + \frac{i_b}{q} \Delta\tau] + \frac{i_s}{q} \Delta\tau + \frac{2K_B T_R \Delta\tau}{q^2 R_L} \tag{5}$$

i_b and i_s are the bulk and surface leakage currents of the APD, q is the charge of an electron, K_B is Boltzman constant, T_R is the effective receiver noise temperature and R_L is the size of the load resistor usad. G is the APD gain (typically 10-300) and F the APD excess noise factor, given by $k_{eff}\, G + (1-k_{eff})(2-1/G)$ where k_{eff} is the effective ratio of hole and electron ionization coefficients (typically $k_{eff} = 0.02$). λ_0 is the average photon absorption rate due to the presence of background radiation. For ideal laser light, the received ppm symbol error probability is given by

$$P_e = 1 - \int_{-\infty}^{\infty} p(v|\lambda_s + \lambda_0) [\int_{-\infty}^{v} p(v'|\lambda_0 + \lambda_s/m) dv']^{Q-1} dv \tag{6}$$

where the quantities p(v|.) are Gaussian probability densities whose mean and variance are given by (4) and (5) and m is the ppm modulation extinction ratio.The effects of fluctuation in the received laser pulse peak intensity are included by averaging (6) with the use of the properly transformed pribability law, (1). No closed form results are possible, numerical integration must be used, and the results obtained depend on the alphabet size, Q , used in the system.

Figure 2 gives dependence of p_e for several values of ψ' on the average number of signal counts per received light pulse for a typical ppm system. An alphabet size Q=16 (L=4) system was assumed to be operated at a source rate of 500 megabits per second so that $\Delta\tau$ = 0.5 ns , and was taken to be 10 photons/sec. Other parameter values used were i_b = 0.1 na, i_s = 10 na , T_R = 600 °K, R_L = 200 Ω and m= 100.

The value of ψ' that charactarises the diode laser light intensity fluctuations can be obtained by directly measuring the mean and variance of the output current of a photodiode exposed to sufficiently intense laser light that an analog output signal results which is considerably larger than the photodiode dark current. Under these conditions, the photodiode output current, i_d , is directly proportional to the incident light instantaneous intensity. If a signal-to-noise ratio is defined as $E^2\{i_d\}/\mathrm{var}\{i_d\}$, then under the probability law (1), the SNR can be expressed as

$$SNR = \frac{(1 + 2\psi')^2}{4\psi'(1 + \psi')} \qquad (7)$$

The SNR approaches inrfinity, as the laser approaches ideal ($\psi' = 0$) behavior. Measured values of ψ' as reported in [7] ranged between 0.001 and 0.005 and correspond to SNR values of 250 and 50 . As can be seen from figures 1 and 2, even these low values of ψ' can cause a substantial degradation in system performance at low ($< 10^{-6}$) symbol error probabilities. A value of $\psi' = 0.1$ (SNR=3) will render the communication system virtually useless.

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List of Figure Captions

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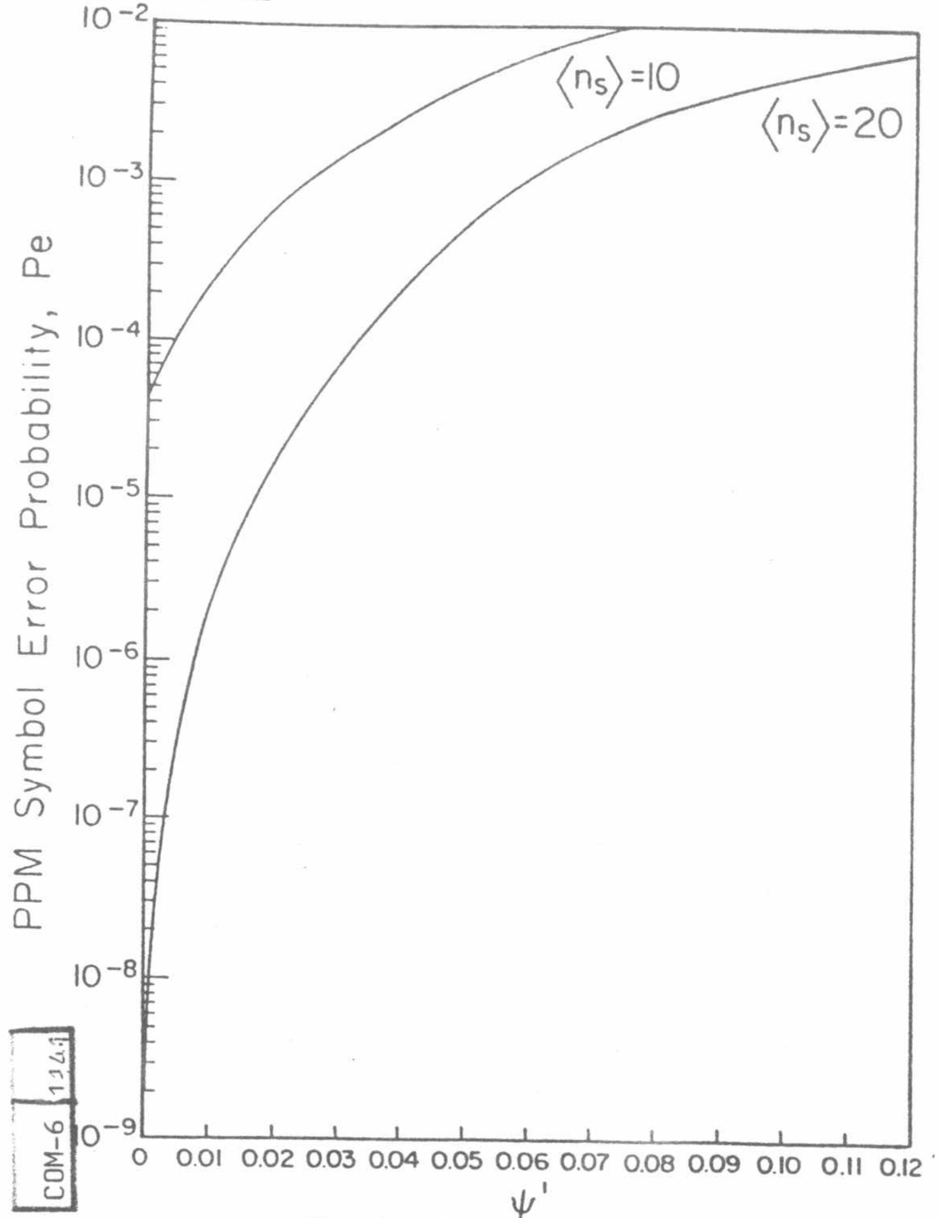

Fig. 1

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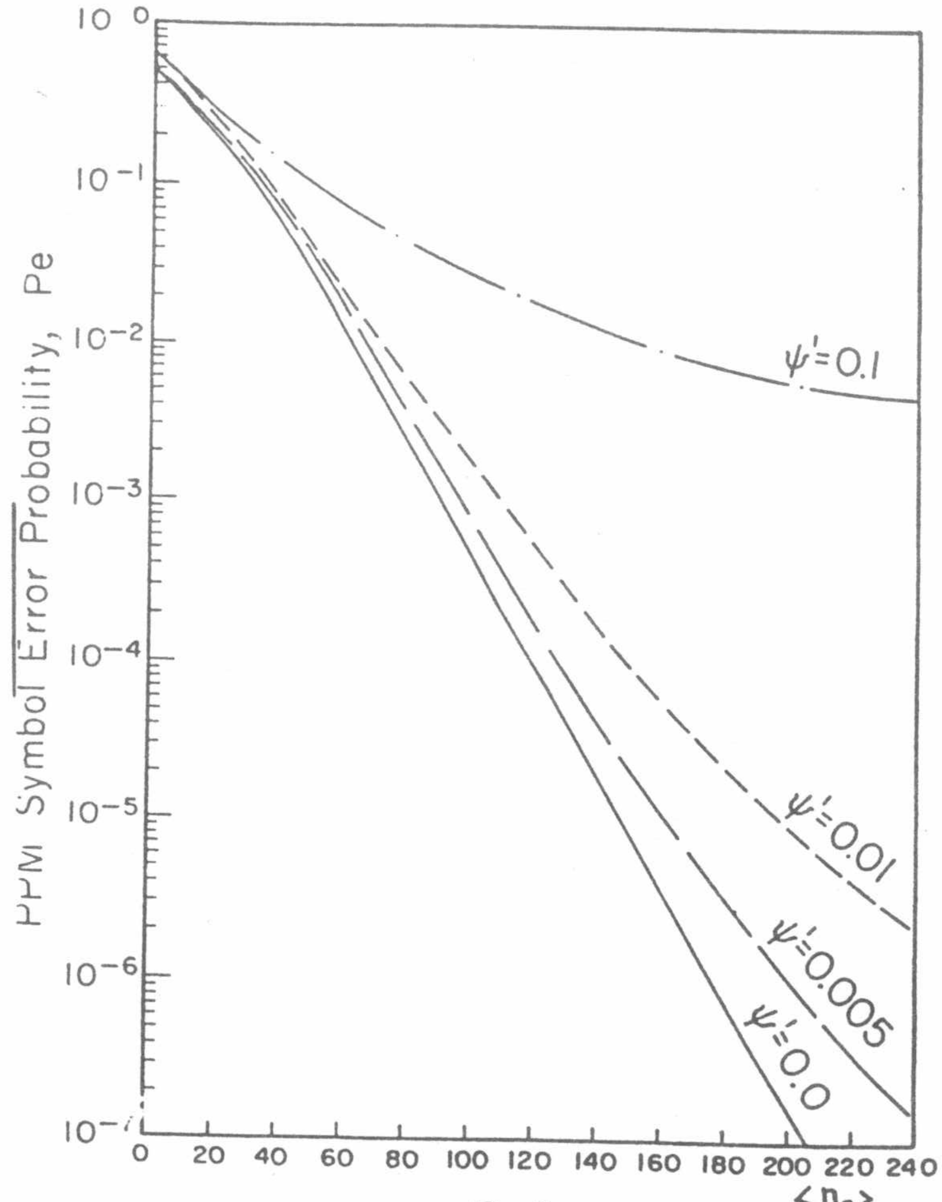

Fig. 2