Analysis of a Homodyne Receiver Using an Injection-Locked Semiconductor Laser

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Abstract—**The purpose of this paper is to study an optical homodyne receiver using an injection-locked semiconductor laser as a local oscillator. The carrier recovery process introduces a phase error and the calculation of its statistical properties leads to the evaluation of the receiver performance. The analysis shows the dependence of the receiver performance on the injected power and the phase detuning between the transmitter and local oscillator electric fields. The receiver performance is affected by both the phase noises of the transmitter and local oscillators as well as by the shot noise of the detectors in the receiver and the modulation noise resulting from the injection locking of the local oscillator by a modulated signal. Within a linear analysis, the receiver sensitivity is shown to be improved by 1.6 dB in comparison with the balanced phase-locked loop for linewidths below 1 MHz. In the case when the overlap of the power spectral density of the message coding and the local oscillator filtering response is very small, the laser linewidth $\Delta\omega$(rads^{-1}) can be as high as 37 $\sqrt{1/T(s)}$, where $T(s)$ is the bit duration in second, the BER is 10^{-10} and the power penalty is 2.4 dB versus ideal detection.**

I. Introduction

ANGULAR modulation of a highly coherent semiconductor laser has proven to be of great interest in coherent communication systems [1]–[3]. Homodyne receivers offer important advantages when compared with their heterodyne counterparts [4]: a 3-dB power sensitivity improvement, a simpler post-detection scheme as the intermediate frequency is null and a reduction of the necessary receiver bandwidth for a given bit rate.

This paper presents a study of an optical homodyne receiver using an injection-locked semiconductor laser as a local oscillator. This receiver represents an alternative to the standard phase-locked loop (PLL) system. Different implementations of the PLL have already been investigated: nonlinear loops [5] and balanced loops [6]. Their common feature is the control of the local oscillator laser by an electrical input. With the injection-locked homodyne receiver, the local oscillator is fed directly with the optical received signal (see Fig. 1). Injection locking occurs provided that the transmitter and local oscillators frequencies are within the locking range determined by the injection rate [7]–[10].

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The application of injection locking to homodyne receivers has been investigated theoretically [11], [12]. However, the formalism used neglects basic phenomena such as the impact of the carrier modulation on the receiver performance, the amplitude-phase coupling in the lasers responsible for the asymmetry of the locking range and the influence of the phase detuning between the transmitter and local oscillator. These effects strongly affect the statistical properties of the phase error. This paper aims at filling this gap.

The analysis of the receiver is carried out by considering the quantum phase noise of the laser transmitter and local oscillator, the phase noise resulting from the locking of the local oscillator by a modulated signal and the shot noise of the detectors. Section II gives a complete description of the homodyne receiver. The different noises affecting the receiver performance are analyzed. Expressions for the parameter characteristic of the receiver performance are given. Adler's modified equation is used in Section III to carry out the analysis describing the behavior of the phase of the locked oscillator. The dynamic processes of the lasers are adiabatically suppressed. With this simplification, the receiver performance is characterized by simple analytical expressions and is compared to the balanced PLL.

II. Problem Outline

Homodyne detection requires the phase recovery of the received signal. This phase recovery process adds a random phase shift to the original optical signal. This results in a phase error at the reception and limits the performance of the homodyne system. With antipodal PSK modulation, the component of the modulated signal at the carrier frequency is totally suppressed and the local oscillator has thus nothing to lock to. In order to transmit both the PSK data signal and a residual carrier, a non-rigorously antipodal phase modulation can be used. This technique is usually referred to as the carrier pilot technique.

Fig. 1 shows a diagram of the homodyne receiver using an injection-locked semiconductor laser and a balanced detection scheme for the PSK signal demodulation. In the following analysis, the lasers are supposed to be emitting continuously in a single mode. A description of the electric field in terms of their complex amplitudes is used.

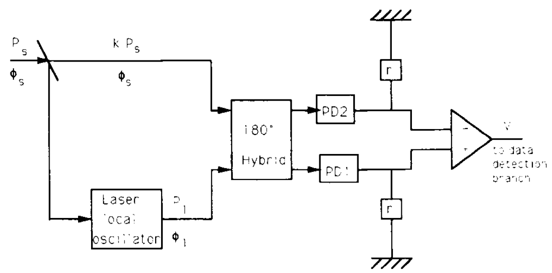

Fig. 1. Schematic diagram of the homodyne receiver using an injection-locked semiconductor laser as a local oscillator.

The optical signal incident on the receiver can be expressed as

$$E_s(t) = \sqrt{P_s(t)} \exp j[\omega_s t + \phi_s(t)] \tag{1}$$

where $P_s(t)$ and $\phi_s(t)$ are the received signal power and phase, respectively. ω_s is the optical frequency of the received signal.

The output field of the *injection-locked* local oscillator may be written as

$$E_1(t) = \sqrt{P_1(t)} \exp j[\omega_s t + \phi_1(t)] \tag{2}$$

where $P_1(t)$ and $\phi_1(t)$ are the local oscillator signal power and phase, respectively. The local oscillator signal and the received signal are recombined in a 3-dB fiber directional coupler acting as a 180° hybrid. The receiver suppresses the dc component produced by the mixing of the data signal and the local oscillator signal on the photodetector area. The output voltage V of the differential amplifier writes [6]

$$V = -2rR\sqrt{kP_sP_1} \cos(\phi_1 - \phi_s) + n_1 - n_2 \tag{3}$$

where r is the load resistor, R is the detector responsivity, and n_1 and n_2 are the shot-noise processes. The parameter k refers to the sharing of power required for the local oscillator locking.

The received signal phase is given by

$$\sigma_s(t) = \phi_i(t) + \phi_{ns}(t) + \phi_a - \pi/2 \tag{4}$$

where $\phi_i(t)$ is the phase-coded signal and $\phi_{ns}(t)$ the quantum phase noise of the received signal. The phase $\phi_{ns}(t)$ undergoes Brownian-motion-type noise because of random spontaneous emission. It has a Gaussian probability distribution [13]. The phase ϕ_a accounts for the mismatch between the arms of the receiver. The constant $\pi/2$ enables us to express the output voltage V in a simple form.

Since the injection locking technique provides a synchronization of the local oscillator frequency to the received signal, homodyning is performed and the receiver can deal with a PSK modulation format. The PSK modulation can be achieved by an external phase modulator or an other injection-locked laser used as a transmitter [14]. The phase carrying the message $\phi_i(t)$ writes

$$\phi_i(t) = \phi\epsilon(t) \tag{5}$$

where ϕ is the phase deviation created by the phase modulator and $\epsilon(t) = \pm 1$ the transmitted data. In order to injection lock the local oscillator, the component of the transmitted signal at the carrier frequency is kept above zero by using a phase shift ϕ smaller than π.

Using (4) and (5) in (3) gives

$$V = 2rR\sqrt{kP_sP_1} [\epsilon \sin\phi \cos\phi_e + \cos(\epsilon\phi) \sin\phi_e] + n_1 - n_2 \tag{6}$$

where the remaining phase error $\phi_e(t)$ is

$$\phi_e(t) = \phi_{ns}(t) - \phi_1(t) + \phi_a \tag{7}$$

or

$$\phi_e(t) = \phi_s(t) - \phi_1(t) - \phi_i(t) + \pi/2. \tag{8}$$

An ideal homodyne receiver would be obtained for $\phi_e(t) = 0$. However, the inevitable noise processes result in the phase error ϕ_e which will eventually limit the overall performance of the receiver. ϕ_a may be adjusted to nullify the stationary value of ϕ_e. In this case, the centered phase error φ_e can be written

$$\varphi_e = \phi_e - \langle\phi_e\rangle = \varphi_{ns} - \varphi_1 \tag{9}$$

where φ_{ns} and φ_1 are the dynamic parts of ϕ_{ns} and ϕ_1, respectively.

In the following analysis, a linearized model of the injection-locked homodyne receiver is developed. For this, a small phase error is required. The voltage V in (6) can be expressed by the sum of three signals [6]

The data signal:	$2rR\sqrt{kP_sP_1}\,\epsilon \sin\phi$
The phase error signal:	$2rR\sqrt{kP_sP_1}\,\phi_e \cos\phi$
And the shot noise signal:	$n_1 - n_2$.

The phase error φ_e is assumed to have a Gaussian probability distribution. In this case, the influence of the phase noise on the receiver performance may be dealt with by considering the phase-error variance $\sigma_e^2 = \langle\varphi_e^2\rangle$.

The local oscillator phase noise writes

$$\varphi_1(t) = \varphi_{n1}(t) + \varphi_0(t) \tag{10}$$

where φ_{n1} is the quantum phase noise of the local oscillator signal which includes the phase-noise influence of the received signal and φ_0 is an additional phase resulting from the transmission of the phase modulation ϕ_i through the locking process. In terms of signal reception, φ_0 can be considered as a noise process.

In the following analysis, the quantum phase noise φ_{ns} and φ_{n1} are assumed to be statistically independent of the modulation process φ_0. Thus, the phase-error variance writes

$$\sigma_e^2 = \langle(\varphi_{ns} - \varphi_{n1})^2\rangle + \langle\varphi_0^2\rangle. \tag{11}$$

The quantum phase noises φ_{ns} and φ_{n1} are correlated since φ_{n1} contains the influence of the received signal noise: the low-frequency part of the power spectral density (PSD) of the locked local oscillator frequency noise turns out to coincide with that of the transmitter laser [15], [16].

In addition to the phase noise, the shot noise affects the receiver performance. It results in errors in the received data. Assuming a Gaussian noise, equally likely symbols and matched-filter detection, the bit error rate (BER) caused by shot noise alone may be written as [17]

$$\text{BER} = \frac{1}{2}\,\text{erfc}\left(\sqrt{\frac{2RkTP_s \sin^2\phi}{e}}\right) \tag{12}$$

where T is the bit duration, e is the electron charge, and erfc denotes the complementary error function. The required power for data transmission P_{sd}, for BER $= 10^{-10}$ and $R = 1$ A/W, is

$$P_{sd} = \frac{1.63\ 10^{-18}}{kT\sin^2\phi}. \tag{13}$$

The flicker noise occurring at low frequencies is caused primarily by laser temperature fluctuations. Its contribution is assumed to be small with the use of a good stabilization system and its influence is neglected in the following analysis.

III. Receiver Performance Analysis

The equation describing the behavior of the locked laser electric field is considered now. The time derivative of the electric fields E_1 inside the laser cavity writes [9]

$$\frac{dE_1(t)}{dt} = \left[-j(\omega_1 - \omega_s) + \frac{1}{2}\left(G_1 - \frac{1}{\tau_{pl}}\right)\right]E_1(t) + \frac{1}{2L}v_g\sqrt{\eta(1-k)}E_s(t) + F_{E1}(t) \tag{14}$$

where ω_s is the optical frequency of the received signal, which is equal to that of the local oscillator under an injection locking condition, ω_1 is the resonant frequency of the local oscillator cavity which is the closest to ω_s, G_1 is the gain per unit time, τ_{pl} is the photon lifetime, L is the length of the local oscillator cavity, and v_g is the group velocity. η represents the fraction of the incident light coupled to the lasing mode. $F_{E1}(t)$ is the Langevin force describing the spontaneous emission.

By separating the real and imaginary parts of (14), the single-mode rate equations for the amplitudes and phases of the local laser field are obtained. Then, the equations are linearized. Gain dynamics are neglected: the intensity of the laser field is assumed instantaneously in equilibrium with the carrier population. $\varphi_1(t)$ and $\varphi_s(t)$ are the deviations of $\phi_1(t)$ and $\phi_s(t)$ from their steady-states values $\langle\varphi_1(t)\rangle$ and $\langle\phi_s(t)\rangle$. The linearized equation for the locked local oscillator phase writes

$$\frac{d\varphi_1}{dt} = \rho(\alpha\sin\theta + \cos\theta)(\varphi_s - \varphi_1) + F_{\phi 1} - \frac{\alpha}{2P_1}F_{pl}. \tag{15}$$

Equation (15) includes a particular feature of semiconductor oscillators which is the amplitude-phase coupling α between intensity and phase fluctuations [18]. Setting α to zero leads to the linearized form of Adler's equation which governs the phase fluctuations of locked microwave oscillators [19]. $F_{\phi 1}$ and F_{pl} are the Langevin forces describing the quantum noise for the phase and intensity. $\langle\theta(t)\rangle$, written θ for simplicity, is the stationary value of the phase detuning $\theta(t)$. It is defined as the difference between the received phase and the locked oscillator phase at the local oscillator input

$$\theta(t) = \phi_s(t) - \phi_1(t) - \phi_a + \pi/2. \tag{16}$$

ρ is Adler's half locking bandwidth [20] and it writes here

$$\rho = \frac{1}{2L}v_g\sqrt{\eta(1-k)P_s/P_1}. \tag{17}$$

The local oscillator frequency detuning, which is the difference between the optical frequency of the master laser and that of the free-running slave laser, may be written as [9]

$$\delta\omega = \rho(\sin\theta - \alpha\cos\theta). \tag{18}$$

The phase detuning θ must belong to the range for which the mode emitted by the local oscillator is stable. Below a critical injection level [21], [22], the whole locking range is stable. The following analysis is restricted to this area: generally, the received power is sufficiently small to be below the critical injection level since for the communication system the lowest allowed power is to be considered. In addition, the use of the receiver above this limit leads to a dramatic reduction of the phase deviation allowed by the system, resulting in an important power penalty.

Therefore, the phase detuning must be within the range $[-\pi/2 + \tan^{-1}\alpha;\ \pi/2]$ for a Fabry–Perot laser [10] and may be even larger for a laser structure with higher mode suppression [23].

Using Fourier analysis, (15) writes:

$$\varphi_1(\omega)[i\omega + \rho(\alpha\sin\theta + \cos\theta)] = \rho(\alpha\sin\theta + \cos\theta)\varphi_s(\omega) + F_{\phi 1}(\omega) - \frac{\alpha}{2P_1}F_{pl}(\omega). \tag{19}$$

A. Phase Noise

The linearized model of the injection-locked homodyne receiver is used in this section to derive the phase-error variance due to the quantum phase noise. As this noise only is considered, the modulator phase deviation ϕ is set to zero.

The PSD of the phase error caused by the quantum phase noise of the transmitter and local oscillator writes

$$S_n(\omega) = \langle(\varphi_{n1}(\omega) - \varphi_{ns}(\omega))(\varphi_{n1}(\omega) - \varphi_{ns}(\omega))^*\rangle \tag{20}$$

where the asterik denotes the complex conjugate.

Since there is no correlation between the *spontaneous* events in the transmitter and local oscillators, (20) can be written as

$$S_n(\omega) = \frac{\omega^2}{\omega^2 + \omega_c^2} [S_1(\omega) + S_s(\omega)]. \quad (21)$$

$S_1(\omega)$ and $S_s(\omega)$ are the phase noise PSD of the transmitter and free-running local oscillator, respectively. They can be related to the 3-dB linewidths of the transmitter and free-running local oscillators, $\Delta\omega_s$ and $\Delta\omega_1$, respectively, by $S_{s\,\mathrm{or}\,1}(\omega) = \Delta\omega_{s\,\mathrm{or}\,1}/\omega^2$. The oscillator phase noises are high-pass filtered. The 3-dB cut-off frequency ω_c writes

$$\omega_c(\theta) = \frac{\partial \delta\omega(\theta)}{\partial \theta}. \quad (22)$$

Then, the phase-error variance caused by the quantum phase noise σ_n^2, can be written

$$\sigma_n^2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_n(\omega)\, d\omega = \frac{\Delta\omega_s + \Delta\omega_1}{2\omega_c}. \quad (23)$$

This result is a generalization of that of Glance [11] and Kikuchi *et al.* [12] derived for $\theta = 0$.

B. Modulation Noise

The phase error ϕ_e contains the terms ϕ_0 accounting for the transmission of the phase modulation through the local oscillator. If the phase modulation is totally reproduced after the local oscillator, the phase shift at the recombination will be independent of the bit value and a decision will be impossible. In other words, the locked laser must filter out the phase modulation. In this section, the quantum noise processes ϕ_{ns}, ϕ_{n1}, and F_i are set to zero.

The output phase of the local oscillator φ_0 can be easily related to the input phase φ_i through the transfer function of the locked local oscillator $H(\omega)$ obtained from (19)

$$H(\omega) = \frac{1}{1 + j\omega/\omega_c}. \quad (24)$$

The cut-off frequency ω_c is given by (22). It decreases with decreasing injection rate ρ or phase detuning θ.

The PSD of the phase error, $S_m(\omega)$, can be related to the transmitted message PSD, $S_i(\omega)$, through

$$S_m(\omega) = \frac{\omega_c^2}{\omega^2 + \omega_c^2} S_i(\omega). \quad (25)$$

The modulation noise is the product of the low-pass filtering of the message. The phase-error variance due to the modulation writes then

$$\sigma_m^2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_m(\omega)\, d\omega. \quad (26)$$

C. Performance

In this section, the influence on the receiver performance of the injection rate, the phase detuning, and the laser linewidths is studied.

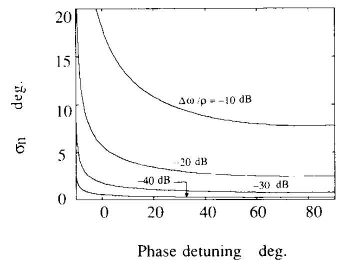

Fig. 2. Phase-error variance caused by quantum phase noise through the locking range. The parameter $\Delta\omega/\rho$ is the mean normalized 3-dB linewidth $(\Delta\omega_s + \Delta\omega_1/2\rho)$.

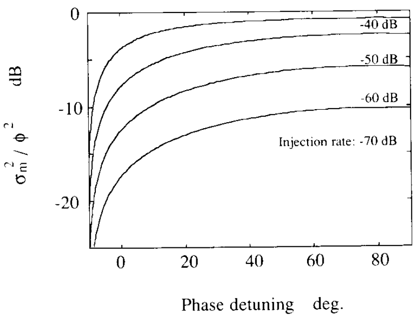

Fig. 3. Phase-error variance caused by modulation noise through the locking range. It is normalized by the modulator deviation ϕ^2. The bit rate is 1 Gbs^{-1}. The injection rate is $\eta(1 - k)P_s/P_1$.

The contribution of the quantum phase noise to the phase error is considered first. In Fig. 2, the square root of the standard deviation σ_n is plotted through the locking range using the normalized linewidth parameter defined as $\Delta\omega/\rho = (\Delta\omega_s + \Delta\omega_1)/2\rho$. In order to minimize the phase-error variance, the locked local oscillator must not be operated near the lower limit of the locking range (lowest values of the phase detuning θ). It can be noticed that high injection levels and low linewidths will be highly beneficial in the system.

Let us now consider the influence of the modulation noise. The phase-error variance σ_m^2 is computed from (26) in the case of a random NRZ bit sequence. Fig. 3 shows the variation of σ_m^2/ϕ^2 through the locking range, where ϕ is the modulation amplitude. The receiver performance increases with decreasing the phase detuning and the injection level. This results from the increase of the filtering action of the local oscillator, expressed in (25). For the same reason, increasing the bit rate results in a reduction of σ_m in Fig. 4. An other way of increasing the receiver efficiency is to choose a coding format which PSD is shifted toward higher frequencies. Fig. 5 illustrates the comparative performances for NRZ and biphase codings. The receiver performance is significantly increased by using a subcarrier modulation of the baseband message spectrum.

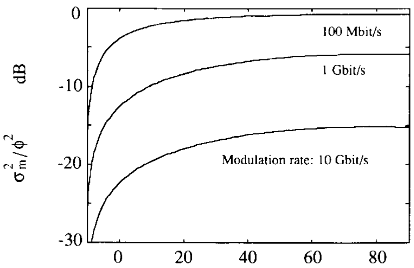

Fig. 4. Phase-error variance caused by modulation noise through the locking range. It is normalized by the modulator deviation ϕ^2. The injection rate is -60 dB.

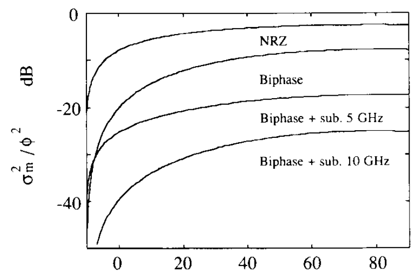

Fig. 5. Phase-error variance caused by modulation noise through the locking range. It is normalized by the modulator deviation ϕ^2. The different modulation formats are NRZ, Biphase and biphase with a subcarrier. The injection rate is -50 dB and the bit rate 1 Gbs^{-1}.

The overall receiver performance is obtained by considering the overall phase-error variance σ_e^2 which may be written

$$\sigma_e^2 = \sigma_n^2 + \sigma_m^2. \tag{27}$$

In order to obtain the best overall receiver performance a compromise between quantum and modulation noise is necessary. In practice, the phase detuning θ can be tuned by adjusting the local oscillator bias current.

In the case of message coding with a random NRZ bit sequence, the overall phase-error variance, obtained from (23) and (26), is given by

$$\sigma_e^2 = \frac{\Delta\omega_s + \Delta\omega_1}{2\omega_c} + \phi^2\left(1 - \frac{1}{\omega_c T} + \frac{1}{\omega_c T}\exp(-\omega_c T)\right) \tag{28}$$

where the term between brackets belongs to the interval [0; 1]. T is the bit time and ω_c is the cut-off frequency given by (22).

Since the cut-off frequency of the local oscillator ω_c has to be small with respect to the bit rate $1/T$ in order to reduce the modulation noise, the overall phase-error variance writes

$$\sigma_e^2 = \frac{\Delta\omega}{\omega_c} + \frac{\phi^2\omega_c T}{2}. \tag{29}$$

By adjusting the phase detuning θ and therefore the local oscillator cut-off frequency ω_c, the minimum value of the phase-error variance

$$\sigma_{\min}^2 = \phi\sqrt{2\Delta\omega T} \tag{30}$$

is obtained for

$$\omega_c^2 = \frac{2\Delta\omega}{\phi^2 T}. \tag{31}$$

For the binary PSK modulation, a rms phase-error variance below 10° is required in order to obtain a BER of 10^{-9} for a power penalty due to phase noise limited to 0.5 dB [24] (the mean phase error may be zero since the phase mismatch between the arms of the receiver can be tuned). Then (30) gives

$$\phi^2 < \frac{4.4\ 10^{-4}}{\Delta\omega T}. \tag{32}$$

By introducing (22) in (31), the phase detuning giving the minimum phase-error variance is given by

$$\theta = \tan^{-1}\alpha + \cos^{-1}\left[\sqrt{\frac{2\Delta\omega}{\phi^2 T(1+\alpha^2)\rho^2}}\right] \tag{33}$$

and exists if

$$\frac{P_s}{P_1} \geq \left(\frac{2Ln_g}{c}\right)^2 \frac{2\Delta\omega}{\phi^2 T(1+\alpha^2)\eta(1-k)}. \tag{34}$$

Using standard laser values: $L = 300\ \mu$m, $n_g = 4.3$, $\alpha = 5$, and $\eta = 0.1$ (34) writes

$$P_s \geq \frac{5.71\ 10^{-23}\Delta\omega}{(1-k)T\phi^2} P_1. \tag{35}$$

The overall receiver sensitivity is the greatest of the two values of the power required for data transmission, P_{sd}, increased by 0.5 dB and the power needed for phase locking, P_s, given by (35). The receiver performance may be optimized by adjusting the amount of optical power flowing through the arms of the receiver, i.e., the value of k. Given the same laser linewidth $\Delta\omega$ and bit duration T, the condition on the phase excursion given by (32) is less critical than for the balanced PLL [6]. Assuming that we remain within the scope of the linear approximation used in the calculations, this results in an improvement of sensitivity of 1.6 dB at low linewidth; in this case, the greatest part of the received power is branched into the reference arm (k can be chosen close to unity). When the linewidth $\Delta\omega$ increases, the sensitivity of the injection locking system relative to the PLL varies as k_{opt}, where k_{opt} is the value of k for which the power required for data trans-

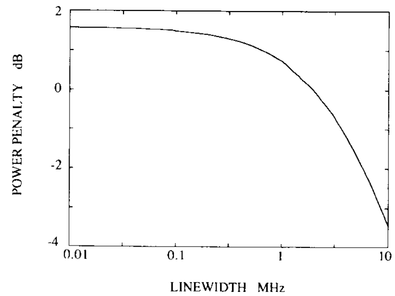

Fig. 6. Power gain of the injection locking receiver in comparison with the balanced phase-locked loop.

mission equals the power needed for phase locking. The injection locking receiver appears to be an improvement over the PLL for linewidths below 1 MHz, as shown in Fig. 6.

In the case when the overlap of the PSD of the message coding and the local oscillator filtering response is small, the receiver performance is limited by the quantum phase noise only.

From (17), (18), and (23), the minimum required power to achieve a rms phase error of 10° writes

$$P_s \geq 2.24\ 10^{-21}\Delta\omega^2 \tag{36}$$

with the numerical values taken above and a phase detuning θ of 40°. Incomplete antipodal phase modulation leads to a power penalty increasing with decreasing magnitude of the phase deviation [6]. A phase deviation $\phi = 50°$ from a static phase detuning of 40° minimizes the receiver penalty to -2.4 dB. The splitting coefficient k for the received power is taken as 98%.

Finally, the receiver requires

$$\Delta\omega^2 T \leq 1.4\ 10^3\ (\text{rad}^2/\text{s}^{-1}). \tag{37}$$

In this case, the laser linewidth $\Delta\omega$ (rad/s^{-1}) can be as high as $37\sqrt{1/T(s)}$ where $T(s)$ is the bit duration in second. For a modulation rate of 1 Gb/s^{-1}, a linewidth as high as 185 kHz satisfies (37).

IV. Conclusions

A linear analysis of an optical homodyne injection-locked receiver has been developed. When a communication system includes such a receiver, a part of the transmitter power is needed to lock the local oscillator and it leads to a power penalty. The influence on the receiver performance of the quantum phase noise and modulation phase noise resulting from the locking of the local oscillator by a phase modulated signal affected by quantum phase noise has been investigated. Not only does the overall performance depend on the injection rate but also on the amplitude-phase coupling and the phase detuning between the transmitter and local oscillator electric fields. The receiver has been shown to act both as a high-pass filter for the quantum phase noise and as a passband filter for the modulation. The cut-off frequency of these filters is a function of the locked phase difference. The choice of the phase mismatch between the two mixed fields is a trade-off between quantum phase noise and modulation noise. We have shown that for high bit rates and laser linewidths below 1 MHz, the injection locking receiver improves the sensitivity by 1.6 dB in comparison with the balanced phase-locked loop. In the case when the overlap of the power spectral density of the message coding and the local oscillator filtering response is very small, the laser linewidth $\Delta\omega$(rad/s^{-1}) can be as high as $37\sqrt{1/T(s)}$, where $T(s)$ is the bit duration in second, the BER is 10^{-10} and the power penalty is 2.4 dB versus ideal detection. The simplicity of this receiver makes it an interesting candidate for PSK system implementation.

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Olivier Lidoyne, photograph and biography not available at the time of publication.

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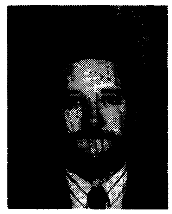

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