Impact of Laser Phase Noise on the Performance of a {3 × 3} Phase and Polarization Diversity Optical Homodyne DPSK Receiver

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***Abstract*—An analysis of the impact of laser phase noise on the performance of a {3 × 3} phase and polarization diversity differential phase-shift keying (DPSK) receiver is done for the phase and shot noise limited case. The results show that, for zero laser linewidths, the maximal signal power penalty of the {3 × 3} phase and polarization diversity DPSK receiver with respect to the conventional heterodyne DPSK receiver is approximately 0.7 dB for $P_e = 10^{-9}$. For nonzero laser linewidths, it appears that depending on the laser linewidth, for large SNR's the performance of the analyzed {3 × 3} phase and polarization diversity DPSK receiver is close to that of the ideal conventional heterodyne DPSK receiver. For a rectangular IF filter, the maximum allowable normalized laser linewidth ($\Delta\nu \cdot T$) for the {3 × 3} phase and polarization diversity DPSK receiver is found to be approximately 0.46% for a power penalty of 1 dB.**

I. Introduction

Coherent optical transmission of digital data has received much attention because of several promising features. In comparison to intensity modulation/direct detection (IM/DD) schemes, coherent optical detection offers a higher selectivity and a higher sensitivity. Homodyning offers the best performance, but it requires an optical phase locked loop in order to phase synchronize the local oscillator laser with the transmitting laser. Since an optical phase locked loop is hard to realize, a solution for this problem is found by using (homodyne/heterodyne) phase diversity receivers where fading of the signal, caused by the phase noise, can be prevented by making use of an optical hybrid [1] and parallel detection of the phase-shifted optical waves [2]–[4]. This results in a minimum penalty for the signal-to-noise ratio (SNR) of approximately 3.0 dB in comparison to homodyne reception and requires a secure optical and electrical signal processing. An other advantage of such a phase diversity receiver is that the photocurrents are already in baseband and baseband circuitry, which is cheaper and easier to implement, is sufficient. A third feature of a phase diversity receiver is that it is able to tolerate relatively large laser linewidths, without excessive performance degradation [5].

A lightwave propagating through a conventional optical fiber has the inconvenience that its polarization state changes at random. Since the performance of a coherent optical receiver highly depends on the (optimal) matching of the polarization state of the received optical wave and the optical wave generated by the local oscillator laser, a polarization controller is necessary to prevent any loss of information due to the random walk of the difference in polarization state of both optical waves. To achieve this purpose there have been found various kinds of solutions. For example, adaptive polarization controllers, the use of polarization maintaining fibers, and the evolving of more complicated polarization insensitive receiver structures [6], [7]. The latter can be realized by means of a polarization diversity technique [2], [8] in which the input light is (equally) decomposed into two orthogonal linear polarization states. The light in both polarization states is detected independently and next processed electronically by identical demodulation schemes.

In this paper we shall investigate the impact of laser phase noise on the performance of a {3 × 3} phase and polarization diversity receiver for the differential phase-shift keying (DPSK) scheme and compare the performance, in terms of the bit-error rate (BER) with the conventional heterodyne DPSK receiver. For the heterodyne receiver we assume perfectly matched polarization states of both optical waves and further identical system parameters. We will express the BER of the receiver analytically and give the numerical results, calculated by means of a computer, for several laser linewidths as a function of the SNR at the IF stage. The receiver has been investigated under the assumption that the local oscillator power is large enough to neglect the noise introduced by the receiver (thermal noise) and let the shot noise related to the local oscillator dominate all other noise sources. Further are assumed, abrupt phase transitions (intersymbol interference is absent) and a high amplitude stability of both lasers in order to be able to neglect the relative intensity noise (RIN) [9]. A conventional {3 × 3} phase diversity receiver using the DPSK (de)modulation scheme [10], [2], is depicted in Fig. 1.

II. The Receiver Structure and Mathematical Representation of the Optical {3 × 3} Phase and Polarization Diversity DPSK Receiver

The model of the analyzed receiver is given in Fig. 2 [2] and consists of two polarization beam splitters, two

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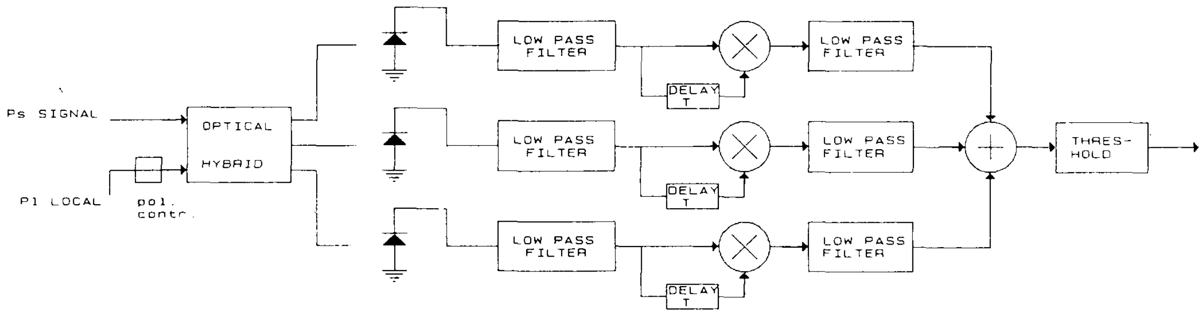

Fig. 1. A {3 × 3} phase diversity receiver employing the DPSK scheme, with a polarization controller in the local oscillator branch of the optical hybrid.

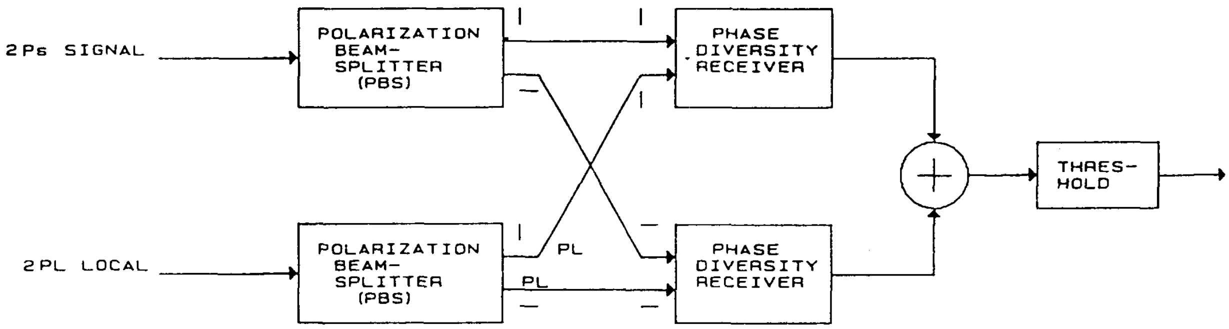

Fig. 2. Model of a polarization diversity receiver consisting of two polarization beam splitters, two phase diversity receivers, an adder, and a threshold comparator.

{3 × 3} DPSK phase diversity receivers as shown in Fig. 1, with two exceptions. The polarization controller can be omitted as well as the threshold comparators. The latter are replaced by a single threshold comparator and the decisions will be made after adding both demodulated data signals from both phase diversity receivers. The light of both the local oscillator and the transmission laser is fed to the polarization beam splitters, where the light is split up between two orthogonal polarization components. Demodulation takes place for each polarization state separately and the results are added and next compared by a threshold detector with a reference level of zero. For proper operation it is desirable to split up the power of the local oscillator equally between the two orthogonal polarization states. This kind of polarization independent or insensitive receivers were earlier introduced by Glance [6], Okoshi and Cheng [11], Kuwahara *et al.* [12], and Cheng *et al.* [13].

In this paper we assume that the light emitted by the local oscillator source is linearly polarized and has a power of $2P_L$ which is equally divided between the two orthogonal polarization states. The local oscillator power is received by three independent photodiodes, which implies that the three receiver branches carry statistically independent shot noise components. We assume the shot noise for all six photodiodes to have a zero mean Gaussian probability density function with variance $\sigma_i^2 = eR\frac{1}{3}P_LB$, where e is the electron charge, B is the receiver bandwidth, and R is the responsitivity of the photodiodes, which is assumed to be equal for all photodiodes used. The phase difference due to phase noise is assumed to have a Gaussian probability density function and zero mean [14]. Since the polarization state of the received optical signal is randomly changing, its power is randomly distributed between both polarization states. The amounts by which the power is split up in the horizontal and vertical polarization states are given by the factor β^2 and $(1 - \beta^2)$, respectively, with $0 \le \beta \le 1$. The photocurrents for the horizontal polarization state including phase and shot noise and omitting the dc terms are given by [2], [13]

$$I_{h,n}(t) = \tfrac{2}{3} R\sqrt{2P_LP_S\beta^2} \cdot b(t) \cdot \cos\left(\omega_{\mathrm{OF}}t + \phi(t) + \rho + \tfrac{2}{3}\pi \cdot n\right) + N_n,$$

with

$$n = 1, 2, 3. \tag{1}$$

ω_{OF} is the radial frequency offset between the transmitting and the local oscillator laser. $\phi(t)$ stands for the phase noises of both the local oscillator and the transmitting laser. ρ stands for the fixed phase shift introduced by the difference in optical path length in the beam splitters for the horizontal polarized light, N_n is the shot noise current in branch n and $b(t)$ is the signaling waveform.

For the photocurrents in the vertical polarization state, we can write

$$I_{v,n}(t) = \tfrac{2}{3} R \sqrt{2P_L P_S(1-\beta^2)} \cdot b(t) \cdot \cos\left(\omega_{OF} t + \phi(t) + \tau + \tfrac{2}{3}\pi \cdot n\right) + N_n',$$

with

$$n = 1, 2, 3. \tag{2}$$

Where τ is the phase shift introduced by the difference in the optical path length in the beam splitters for the vertical polarized light and N_n' is the shot noise current in branch n.

The demodulated signal at the input of the threshold comparator at the sampling moment can now simply be expressed by the following equation under the assumption of ideal filtering:

$$V_{\text{threshold}}(kT) = c \sum_{n=1}^{3} \left\{ I_{h_n}(t) \cdot I_{h_n}(t-T) + I_{v_n}(t) \cdot I_{v_n}(t-T) \right\}, \quad k = 0, 1, 2, 3 \cdots \tag{3}$$

where T is the delay time, which for DPSK modulation is equal to the bit time, kT is the sampling moments, c is a constant, and $(n+1)$ is the number of receiver branches in each phase diversity receiver. In order to express $V_{\text{threshold}}$ in two sums of squared variables, we make a change of variables. To express $V_{\text{threshold}}$, we make use of conventional analysis [15], which for a similar purpose was earlier introduced by Cheng *et al.* [13]. We define 12 variables divided into two sets, which consist of a linear combination of the above mentioned six photocurrents.

Set 1. $(\bar{u} = (u_1, u_2, u_3, u_4, u_5, u_6))$

$$\begin{aligned} u_1 &= I_{v_1}(t) + I_{v_1}(t-T) \\ u_2 &= I_{v_2}(t) + I_{v_2}(t-T) \\ u_3 &= I_{v_3}(t) + I_{v_3}(t-T) \\ u_4 &= I_{h_1}(t) + I_{h_1}(t-T) \\ u_5 &= I_{h_2}(t) + I_{h_2}(t-T) \\ u_6 &= I_{h_3}(t) + I_{h_3}(t-T). \end{aligned} \tag{4}$$

Set 2. $(\bar{s} = (s_1, s_3, s_3, s_4, s_5, s_6))$

$$\begin{aligned} s_1 &= I_{v_1}(t) - I_{v_1}(t-T) \\ s_2 &= I_{v_2}(t) - I_{v_2}(t-T) \\ s_3 &= I_{v_3}(t) - I_{v_3}(t-T) \\ s_4 &= I_{h_1}(t) - I_{h_1}(t-T) \\ s_5 &= I_{h_2}(t) - I_{h_2}(t-T) \\ s_6 &= I_{h_3}(t) - I_{h_3}(t-T). \end{aligned} \tag{5}$$

Rewriting $V_{\text{threshold}}$ in terms of these variables leads to the following equation:

$$\begin{aligned} V_{\text{threshold}} &= \tfrac{1}{4} \cdot c \cdot \left((u_1^2 + u_2^2 + u_3^2 + u_4^2 + u_5^2 + u_6^2) - (s_1^2 + s_2^2 + s_3^2 + s_4^2 + s_5^2 + s_6^2) \right) \\ &= \tfrac{1}{4} \cdot c \cdot (r_1^2 - r_2^2) \end{aligned} \tag{6}$$

where

$$r_1^2 = (u_1^2 + u_2^2 + u_3^2 + u_4^2 + u_5^2 + u_6^2) \tag{7}$$

and

$$r_2^2 = (s_1^2 + s_2^2 + s_3^2 + s_4^2 + s_5^2 + s_6^2). \tag{8}$$

The prior probability of sending a mark is assumed to be equal to that of sending a space. The conditional bit-error probability for receiving a space provided a mark was sent $\{P(V_{\text{threshold}} < 0 \mid \text{"mark" sent})\}$ is in terms of r_1^2 and r_2^2 the probability that $r_1^2 < r_2^2$, implying that $V_{\text{threshold}} < 0$. This probability is equal to $P(V_{\text{threshold}} > 0 \mid \text{"space" sent})$ because of symmetry. These conditional error probabilities imply that the phase difference due to the phase noise, is assumed to vary little within one bit period

$$\begin{aligned} P_e(\text{"mark"}) &= \tfrac{1}{2} \cdot \text{prob}\left\{ r_1^2 < r_2^2 \right\} \\ &= \tfrac{1}{2} \cdot \text{prob}\left\{ r_1 < r_2 \right\}. \end{aligned} \tag{9}$$

If $f_1(r_1)$ is the probability density function of r_1 and $f_2(r_2)$ is the probability density function of r_2, we can write for the overall error probability $\{P_e(\text{"mark"}) + P_e(\text{"space"})\}$ of the receiver in the shot noise limited case [2]

$$P_e = \int_0^\infty f_1(r_1) \int_{r_1}^\infty f_2(r_2)\, dr_2\, dr_1. \tag{10}$$

The variables r_1 and r_2, respectively, can be regarded as the norm of a six-dimensional vector. The probability density function of the norm of a six-dimensional vector $\langle |\bar{r}| \rangle = \langle |(x, y, z, r, s, t)| \rangle \triangleq A$ where

$$A = \sqrt{(\bar{x}^2 + \bar{y}^2 + \bar{z}^2 + \bar{r}^2 + \bar{s}^2 + \bar{t}^2)}$$

and all the components have a Gaussian probability density function, the same variance and fixed mean values, can be expressed by the noncentral chi distribution function with 6 degrees of freedom [16]

$$f(r) = \frac{r^3}{A^2\sigma^2} \cdot I_2\left[\frac{Ar}{\sigma^2}\right] \cdot \exp\left[-\frac{r^2 + A^2}{2\sigma^2}\right] \quad (11)$$

where $I_2[\cdot]$ stands for the modified Bessel function of the first kind and σ^2 is equal to the variance. Since the equation for the bit-error probability of the diversity receiver is a double integral, without taking into account the phase noise, we have two different six-dimensional vectors each with its own norm A_1 and A_2, respectively

$$A_1 = \sqrt{(\bar{u}_1^2 + \bar{u}_2^2 + \bar{u}_3^2 + \bar{u}_4^2 + \bar{u}_5^2 + \bar{u}_6^2)} \quad (12a)$$

and

$$A_2 = \sqrt{(\bar{s}_1^2 + \bar{s}_2^2 + \bar{s}_3^2 + \bar{s}_4^2 + \bar{s}_5^2 + \bar{s}_6^2)}. \quad (12b)$$

We can rewrite the photocurrents and their delayed version in terms of the phase difference $\Delta\Phi$, where $\Delta\Phi$ is defined according to the following equation:

$$\Delta\Phi \triangleq \phi(t) - \phi(t - T) \quad (13)$$

and $\phi(t)$ is the phase noise defined below (1). We assume that the phase difference has a Gaussian distribution function with a zero mean value and a variance σ_ϕ^2, which is directly related to the sum of the linewidths of the local oscillator laser and the transmitting laser according to the following relation [17]:

$$\sigma_\phi^2 = 2\pi \cdot (\Delta\nu_{\text{LO}} + \Delta\nu_{\text{TRANS}}) \cdot T = 2\pi\Delta\nu_{\text{tot}}T. \quad (14)$$

Here $\Delta\nu_{\text{LO}}$ and $\Delta\nu_{\text{TRANS}}$ are the full-width half-maximum FWHM laser linewidths of the local oscillator laser and the transmitting laser, respectively. Rewriting the photocurrents in terms of the phase difference $\Delta\Phi$ leads to the following equations:

$$\begin{aligned} I_{h,n}(t) &= \tfrac{2}{3} R\sqrt{2P_LP_S\beta^2} \cdot b(t) \\ &\quad \cdot \cos(\omega_{\text{OF}}t + \Delta\Phi + \phi(t - T) \\ &\quad + \rho + \tfrac{2}{3}\pi \cdot n) + N_n \\ I_{v,n}(t) &= \tfrac{2}{3} R\sqrt{2P_LP_S(1 - \beta^2)} \cdot b(t) \\ &\quad \cdot \cos(\omega_{\text{OF}}t + \Delta\Phi + \phi(t - T) \\ &\quad + \tau + \tfrac{2}{3}\pi \cdot n) + N_n', \qquad n = 1, 2, 3. \end{aligned} \quad (15)$$

The norms A_1 and A_2 can now easily be computed according to (4), (5), (12a), and (12b). This results in

$$A_1 = \frac{4}{3}\sqrt{3}R\sqrt{P_LP_S} \cdot \cos\left(\frac{\Delta\Phi}{2}\right) \quad (16)$$

and

$$A_2 = \frac{4}{3}\sqrt{3}R\sqrt{P_LP_S} \cdot \sin\left(\frac{\Delta\Phi}{2}\right). \quad (17)$$

Rewriting (11) and taking into account the phase and shot noise leads to the following equation:

$$P_e = \frac{1}{\sqrt{2\pi} \cdot \sigma_\phi} \cdot \int_{-\infty}^{\infty} \exp\left[\frac{-\Delta\Phi^2}{2\sigma_\phi^2}\right] \cdot \int_0^\infty f_1(r_1) \int_{r_1}^\infty f_2(r_2)\, dr_1 \cdot dr_2 \cdot d(\Delta\Phi) \quad (18)$$

where $f_1(r_1)$ and $f_2(r_2)$ are the bit-error probability density functions in terms of A_i, r_i, and σ_i $\{i = 1, 2\}$ given by the following equations:

$$f_1(r_1) = \frac{r_1^3}{A_1^2\sigma_1^2} \cdot I_2\left[\frac{A_1r_1}{\sigma_1^2}\right] \cdot \exp\left[-\frac{r_1^2A_1^2}{2\sigma_1^2}\right] \quad (19)$$

$$f_2(r_2) = \frac{r_2^3}{A_2^2\sigma_2^2} \cdot I_2\left[\frac{A_2r_2}{\sigma_2^2}\right] \cdot \exp\left[-\frac{r_2^2A_2^2}{2\sigma_2^2}\right]. \quad (20)$$

The local oscillator photons are randomly distributed between both polarization states by the polarization beam splitters. For this reason, the shot noises introduced by the local oscillator laser in the receiver for the horizontal and the vertical polarization state, are statistically independent and have Gaussian probability density functions with zero mean and variance $\sigma_0^2 = eBRP_{\text{LO}} \triangleq \langle N_n^2 \rangle = \langle N_n'^2 \rangle$ $\{n = 1, 2, 3\}$. $\sigma_1^2 = \sigma_2^2$ and according to (11) equal to $2/3 \cdot \sigma_0^2$. The SNR of the $\{3 \times 3\}$ phase and polarization diversity DPSK receiver can be calculated to give

$$\gamma = \frac{2\eta P_sT}{h\nu} \quad (21)$$

which in our case of ideal filtering, is identical to the average number of signal photons per bit time T, called N. Next we make the following substitutions in (18) and (19):

$$s \triangleq \frac{\Delta\Phi}{\sqrt{2}\sigma_\phi}$$

$$t \triangleq \frac{r_1}{2\sigma_1} \quad (22)$$

$$\frac{A_1}{\sigma_1} = 2\sqrt{2\gamma} \cdot \cos\left(\frac{\sigma_\phi s}{\sqrt{2}}\right) \triangleq 2\alpha \quad (23)$$

with

$$\alpha \triangleq \sqrt{2\gamma} \cdot \cos\left(\frac{\sigma_\phi s}{\sqrt{2}}\right). \quad (24)$$

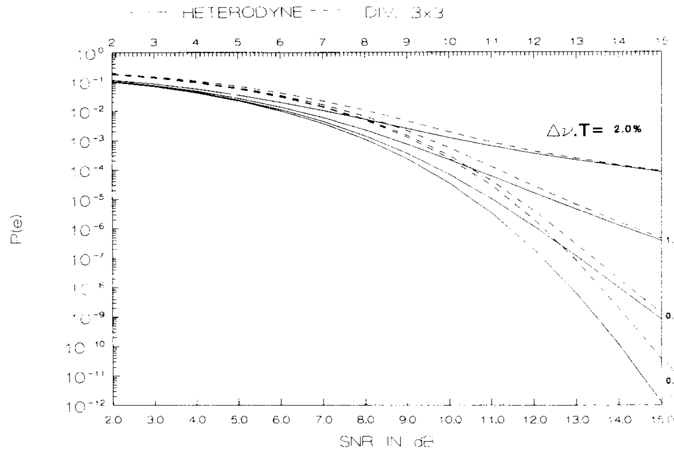

Fig. 3. The BER versus the SNR for various normalized laser linewidths of the ideal heterodyne and the {3 × 3} phase and polarization diversity DPSK receiver.

In a similar way we make the following substitutions in (20)

$$u \triangleq \frac{r_2}{2\sigma_2} \tag{25}$$

$$\frac{A_2}{\sigma_2} = 2\sqrt{2\gamma} \cdot \sin\left(\frac{\sigma_\phi s}{\sqrt{2}}\right) \triangleq 2\beta \tag{26}$$

with

$$\beta \triangleq \sqrt{2\gamma} \cdot \sin\left(\frac{\sigma_\phi s}{\sqrt{2}}\right). \tag{27}$$

Substitution of the variables given in (22) to (27) results in the bit-error probability for the analyzed {3 × 3} phase and polarization diversity DPSK receiver. This as a function of the SNR (γ), which is a parameter of $\alpha(\gamma, s)$ and $\beta(\gamma, s)$ and directly related to the average number of signal photons/bit (see (21)).

$$P_e = \frac{4}{\sqrt{\pi}} \int_{-\infty}^{\infty} e^{-s^2} \int_0^{\infty} \frac{t^3}{\alpha^2} I_2[2\alpha t]\, e^{-[t^2+\alpha 2]} \cdot \int_t^{\infty} \frac{u^3}{\beta^2} I_2[2\beta u]\, e^{-[u^2+\beta 2]} \cdot du \cdot dt \cdot ds. \tag{28}$$

III. The Performance of the {3 × 3} Phase and Polarization Diversity DPSK Receiver in Comparison to the Conventional Heterodyne DPSK Receiver

For nonzero laser linewidths we computed the integral (28) numerically for several laser linewidths. The results are depicted in Fig. 3 as a function of the SNR (in decibels) and the normalized laser linewidth $\Delta\nu \cdot T$. In this figure are also depicted the BER curves of the ideal conventional heterodyne DPSK receiver according to [18]. This is done for reasons of comparison. Notice that when we speak about the linewidth, we mean the sum of the linewidths of the local oscillator and the transmitting laser.

For a normalized laser linewidth of 0.2% ($= \Delta\nu \cdot T$), the results are within 0.5 dB from the phase noise free case. For the heterodyne DPSK receiver (receiver I) it results in an excess power penalty of 0.45 dB with respect to the shot noise limited case, for the diversity receiver (receiver II) the excess power penalty is less than 0.5 dB. For a normalized linewidth ($\Delta\nu \cdot T$) of 0.5%, the BER curves of receiver II approaches the BER curve of receiver I for large SNR's in the shot and phase noise limited case. For a normalized laser linewidth of 1.0% the BER curve of receiver II inclines to that of receiver I for SNR's > 13 dB. For even larger values of $\Delta\nu \cdot T$, the performances of both receivers are almost identical for SNR's larger than approximately 11 dB. From the BER curves depicted in Fig. 3 one can conclude that the curves for $\Delta\nu \cdot T$ is 1.0 and 2.0% of both receivers start to bottom out for large SNR's, implying the existence of an error floor, caused by the phase noise. An increase of the signal power will not result in a better BER and for this reason these receivers are useless for large laser linewidths in practical situations. These BER floors can be easily derived using the irreducible error probability expression as a function of the normalized laser linewidth [19]

$$P_e = \text{erfc}\left[\frac{\sqrt{\pi}}{4 \cdot \sqrt{\Delta\nu \cdot T}}\right]. \tag{29}$$

The error floor according to (29) is plotted in Fig. 4 for normalized laser linewidths varying from 0.2 to 2.0%.

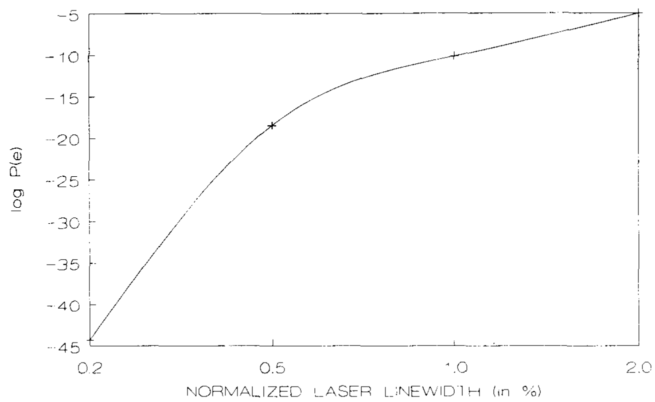

Fig. 4. The saturation bit-error-rate as a function of the normalized laser linewidth.

For zero laser linewidth (28) can be rewritten to give

$$P_e = \frac{\bar{e}^N}{64} \cdot (32 + 12 \cdot N + N^2) \qquad (30)$$

with N as the number of signal photons per bit. It is found that the SNR required to achieve $P_e = 10^{-9}$ is 13.66 dB which is equivalent to 23.2 photons per bit. This result is similar with [2, eq (57)].[1] In comparison to the heterodyne DPSK receiver which requires 20 photons per bit (13.0 dB), this results in a signal power penalty of approximately 0.7 dB [2].

We choose as criteria for the maximum allowable laser linewidth in the analyzed coherent receivers that linewidth which increases the signal power P_s required for the receiver to achieve $P_e = 10^{-9}$ by maximal 1.0 dB. Computation of (28) for an SNR of 14.66 dB and a BER of 10^{-9} results for the $\{3 \times 3\}$ phase and polarization diversity DPSK receiver in a maximum allowable normalized laser linewidth up to approximately 0.46%, while the conventional heterodyne DPSK receiver (see [18, eq. (36)]) can only tolerate normalized laser linewidths up to approximately 0.36%. This for the phase and shot noise limited case and optimal signal processing for all branches of the phase diversity receiver depicted in Fig. 1. Further is assumed that the radial frequency offset ω_{OF} is kept small.

IV. Discussion

The maximum tolerable linewidths for both receivers have been derived for a rectangular IF filter. Some comparison with [19] shows that an optimum IF filter can be found for the heterodyne DPSK receiver, which differs from the rectangular. This results in an increase in the maximum tolerable linewidth by approximately 1.5 times. With the latter in mind, we expect that optimum IF filters for the $\{3 \times 3\}$ phase and polarization diversity DPSK receiver will result in an increase of the maximum tolerable linewidth by approximately the same amount.

[1]The coefficient of N^2 differs by a factor of 2. However, (30) has been confirmed by the authors of [2].

V. Conclusion

The analysis shows that it is possible to decrease the influence of the phase noise and polarization fluctuations by using diversity techniques, which however introduce a signal power penalty with respect to the heterodyne DPSK receiver of approximately 0.7 dB in the shot noise limited case. For nonzero laser linewidths the performance of the $\{3 \times 3\}$ phase and polarization diversity receiver approaches the performance of the conventional heterodyne DPSK receiver for large SNR's. The maximum tolerable normalized laser linewidth ($\Delta\nu \cdot T$) for the diversity receiver turned out to be 0.46%, this in comparison to 0.36% for the conventional heterodyne DPSK receiver.

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