TABLE 3 Measured Efficiencies

	P_{DC} (W)	P_{add} (mW)	Gain (dB)	η (%)
Cascaded	1.6	14.1	26	0.88
Balanced	1.6	29.5	12.6	1.84
Novel	1.6	19.9	25	1.24

thermore, if the conventional balanced configuration is used the mismatch will be even worse than for the individual amplifier. This is because the power reflected back to the input will be the input power amplified once and then reflected by the amplifiers to the input port. By the introduction of two 90° sections the input mismatch is reduced to the input mismatch of the individual amplifier.

MEASUREMENTS

To verify the principle the balanced, cascaded, and proposed configurations have been measured for the cases of low and high gain individual amplifiers. The same amplifier, coupler, and filter modules have been used for all configurations. Center frequency was 4.8 GHz. The loss of the filter was 0.5 dB.

The results of the power measurements are shown in Figures 3 and 4. The 1-dB compression points are shown in Table 1. The low power output of the balanced configuration is due to the 1-dB gain difference between amplifiers.

The measured signal responses of the three configurations at center frequency are shown in Table 2, and the measured efficiencies of the different configurations are shown in Table 3.

CONCLUSION

to obtain output power and efficiency comparable to that of a balanced configuration and at the same time the gain of a cascade configuration.

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IMPACT OF LOCAL OSCILLATOR INTENSITY NOISE ON THE PERFORMANCE OF THE OPTICAL PHASE-DIVERSITY FSK RECEIVER USING DELAY-AND-MULTIPLYING DISCRIMINATOR

Yang-Han Lee, Ching-Chih Kuo, and Hen-Wai Tsao
Department of Electrical Engineering
National Taiwan University
Taipei, Taiwan, Republic of China

KEY TERMS

Optical communication, frequency modulation, discriminator, noise

ABSTRACT

The impact of local oscillator intensity noise on the performance of an optical phase-diversity FSK receiver using a delay-and-multiplying discriminator is analyzed. Given the data rate, frequency deviation, laser linewidth, RIN noise, and thermal noise, we can obtain the minimum received signal power together with the corresponding optimal local oscillator power to achieve the required BER. Numerical results with system parameters given in [1] show that $(P_L)_{opt}$ *is* -1.46 *dBm for RIN =* -160 *dB/Hz and* -6.4 *dBm for RIN =* -150 *dB/Hz when the thermal noise is* 9×10^{-24} *A²/Hz.*

INTRODUCTION

The local oscillator relative intensity noise (RIN), caused by random fluctuations of the optical power of both the transmitting and local oscillator (LO) lasers, may have a significant influence on the performance of phase-diversity receivers [1, 2].

The impact of local oscillator RIN on the performance of a phase-diversity ASK receiver has been analyzed in [1, 3]. The phase-diversity FSK receiver [4, 5] also suffers from the LO RIN. In this letter, we use the Gaussian approximation [6] to analyze the impact of RIN on the performance of the phase-diversity FSK receiver.

For a coherent system with negligible RIN or with a balanced receiver structure [7], the system performance can approach the shot noise limit as the LO power increases to suppress the thermal noise. However, when the RIN is not negligible, increase of LO power tends, on the one hand, to alleviate the degradation caused by the thermal noise, but, on the other hand, to increase the degradation due to the RIN. So there should exist an optimal LO power to meet the required system performance, i.e., the specified BER.

RECEIVER SYSTEM MODEL

Figure 1 is the diagram of an optical phase diversity FSK receiver [4–6]. The 90° optical hybrid has two inputs: One is the received optical field given by

$$E_s(t) = \sqrt{2P_s}\cos(\omega_c t + \Phi_m(t) + \Phi_T(t)), \tag{1}$$

and the other, assumed to have the same polarization as $E_s(t)$, is the LO oscillator field given by

$$E_L(t) = \sqrt{2P_L}\cos(\omega_L t + \Phi_L(t)), \tag{2}$$

where P_s and P_L are the received signal and LO powers, respectively. ω_c and ω_L are the frequencies of the received and LO optical carriers, respectively. $\Phi_T(t)$ and $\Phi_L(t)$ are the phase noise of the transmitting and LO lasers, respectively. $\Phi_m(t)$ is the angle modulation given by

$$\begin{aligned}\Phi_m(t) &= 2\pi f_d \int_0^t m(t')\,dt' \\ &= 2\pi f_d \int_0^t \left(\sum_{k=-\infty}^{\infty} a_k p(t' - kT)\right) dt', \end{aligned} \tag{3}$$

where a_k is the input data stream, f_d is the frequency deviation, $p(t)$ is a pulse function satisfying the Nyquist criterion [8]: $p(0) = 1$, $p(mT) = 0$ for any nonzero integer m. The raised cosine waveform [9] is a well-known example. And T is the bit duration ($R_b = 1/T$: data rate).

As shown in [6], we may obtain the signal-to-noise ratio (SNR) at the output of the LPF_B as,

$$\mathrm{SNR} = \frac{(f_d/R_b)^2}{\Delta\nu/\pi R_b + y((f_d/R_b)^2 + \Delta\nu/\pi R_b + \frac{1}{3}) + \frac{2}{3}y^2} \tag{4}$$

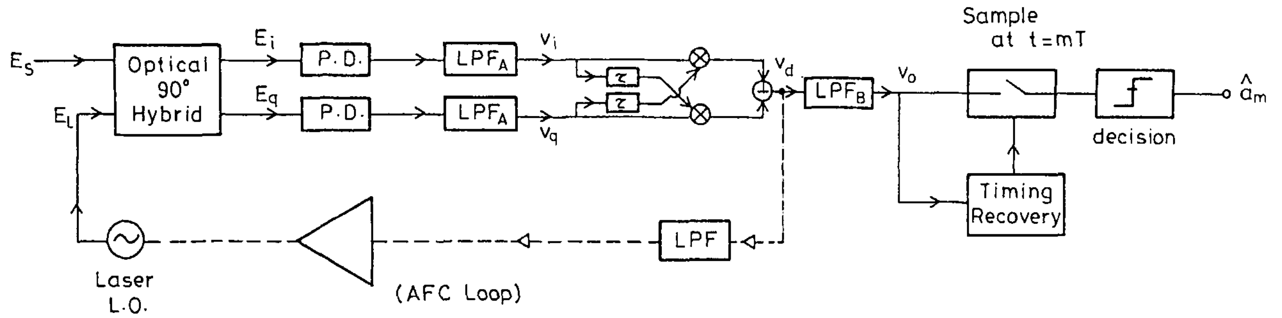

Figure 1 The system block diagram of a phase-diversity FSK system

where y is defined as

$$y = \frac{(2qRP_L/N + \langle i_{\rm th}^2\rangle + (RP_L)^2\gamma/N^2)R_b}{R^2P_sP_L}$$
$$= \frac{(2q/N + \langle i_{\rm th}^2\rangle/RP_L + RP_L\gamma/N^2)R_b}{RP_s}, \qquad (5)$$

where q is the electronic charge, $\langle i_{\rm th}^2\rangle$ represents the thermal noise spectral density of the preamplifier at the IF stage, N is the number of receiver branches, and $\Delta\nu$ is the sum of the transmitting and LO laser linewidths. The first term in (5) represents the shot noise. The second term represents the thermal noise. The third term represents the LO RIN where

$$\text{RIN} = 10\log\gamma \quad \text{in} \quad \text{dB/Hz}. \qquad (6)$$

The bit error rate based on the Gaussian approximation (BER) is given as

$$\text{BER} = Q(\sqrt{\text{SNR}}), \qquad (7)$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-\alpha^2/2}\,d\alpha = \frac{1}{2}\,\text{erf}\,c\left(\frac{x}{\sqrt{2}}\right).$$

DERIVATION OF OPTIMUM P_{LO} AND MINIMUM RECEIVER SENSITIVITY P_s

From (4), we can express the parameter y in terms of SNR, f_d, R_b, $\Delta\nu$ as

$$y = -\frac{3}{4}\left(\left(\frac{f_d}{R_b}\right)^2 + \frac{\Delta\nu}{\pi R_b} + \frac{1}{3}\right) + \frac{1}{4}\sqrt{9\left(\left(\frac{f_d}{R_b}\right)^2 + \frac{\Delta\nu}{\pi R_b} + \frac{1}{3}\right)^2 - 24\left(\frac{\Delta\nu}{\pi R_b} - \frac{(f_d/R_b)^2}{\text{SNR}}\right)}. \qquad (8)$$

From the definition of y in (5), we obtain the received signal sensitivity P_s as

$$P_s = \frac{(2q/N + \langle i_{\rm th}^2\rangle/RP_L + RP_L\gamma/N^2)R_b}{Ry}. \qquad (9)$$

Taking the derivative of P_s in (9) with respective to P_L and setting it to be zero, we can obtain the optimal LO power together with the minimum receiver sensitivity, respectively, as

$$(P_L)_{\rm opt} = \frac{N}{R}\sqrt{\frac{\langle i_{\rm th}^2\rangle}{\gamma}}, \qquad (10)$$

$$(P_s)_{\rm min} = \frac{2R_b(q + \sqrt{\gamma\langle i_{\rm th}^2\rangle})}{NRy}, \qquad (11)$$

where for a specified BER (and thus SNR), y can be obtained from (8).

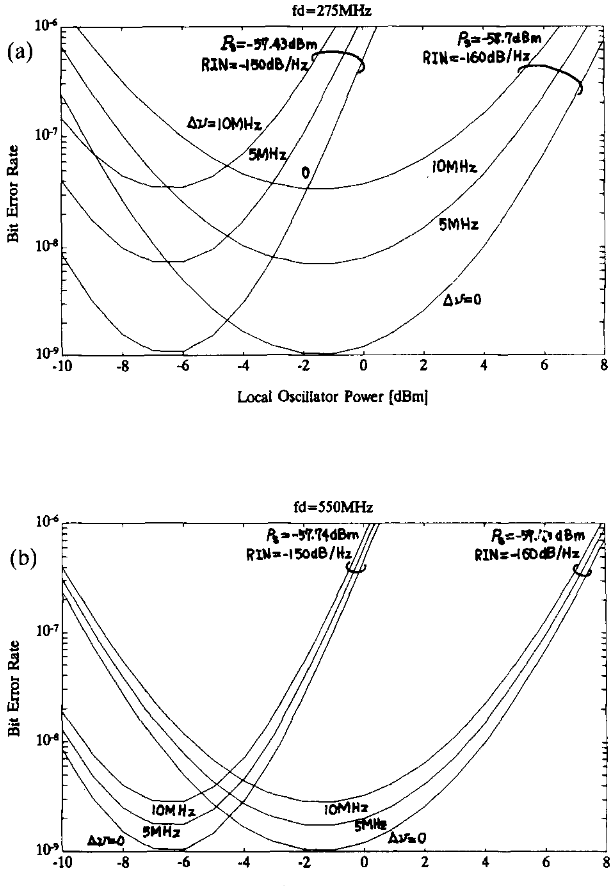

Figure 2 Bit error rate (BER) vs the local oscillator power (P_L) for (a) f_d = 275 MHz, P_s = −57.43 dBm of RIN = −150 dB/Hz, and P_s = −58.7 dBm of RIN = −160 dB/Hz; (b) f_d = 550 MHz, P_s = −57.74 dBm of RIN = −150 dB/Hz, and P_s = −59.02 dBm of RIN = −160 dB/Hz in terms of $\langle i_{\rm th}^2\rangle = 9 \times 10^{-24}\,A^2/\text{Hz}$ and $\Delta\nu$ = 0, 5 MHz, 10 MHz, respectively

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NUMERICAL EXAMPLE

Consider a typical data link: Data rate R_b = 150 Mbits/sec, R = 0.84 A/W, $\Delta\nu$ = 0, 5 MHz, 10 MHz, $\langle i_{th}^2 \rangle = 9 \times 10^{-24}$ A^2/Hz [1], N = 2 (for a 90° optical hybrid, f_d = 275 MHz and 550 MHz. To meet BER = 10^{-9}, the SNR should be around 36 for Gaussian approximation.

The BER versus the local oscillator power (P_L) for f_d = 275 MHz, P_s = −57.43 dBm of RIN = −150 dB/Hz, and P_s = −58.7 dBm of RIN = −160 dB/Hz are shown in Figure 2(a); f_d = 550 MHz, P_s = −57.74 dBm of RIN = −150 dB/Hz, and P_s = −59.02 dBm of RIN = −160 dB/Hz are shown in Figure 2(b). In Figure 2, we use the P_S to be equal to $P_{\min}$ at BER = 10^{-9} and $\Delta\nu$ = 0 from (11). We find there exists an optimal local power which can be found from (10).

From (8) and (11) with BER specified as 10^{-9}, the minimum receiver signal power $(P_S)_{\min}$ as a function of RIN for f_d = 275 MHz and f_d = 550 MHz are shown in Figures 3(a) and 3(b), respectively. The minimum received signal power increases as the RIN and the laser phase noise increase. When f_d = 275 MHz, $(P_s)_{\min}$ = −58.7 dBm for $\Delta\nu$ = 0 and RIN = −160 dB/Hz (point A); $(P_s)_{\min}$ = −57.43 dBm for $\Delta\nu$ = 0 and RIN = −150 dB/Hz (point B) as shown in Figure 3(a). When f_d = 550 MHz, $(P_s)_{\min}$ = −59.02 dBm for $\Delta\nu$ = 0 and RIN = −160 dB/Hz (point a); $(P_s)_{\min}$ = −57.74 dBm for $\Delta\nu$ = 0 and RIN = −150 dB/Hz (point b) as shown in Figure 3(b). The optimal LO power $(P_L)_{\rm opt}$ as a function of RIN for $\langle i_{th}^2 \rangle = 9 \times 10^{-24}$ A^2/Hz and R = 0.84 A/W are shown in Figure 4. The optimal LO power decreases as the RIN increases. It is also noted that $(P_L)_{\rm opt}$ is independent of y, thus independent of f_d, R_b, $\Delta\nu$, and SNR [see Eq. (7)]. We can find $(P_L)_{\rm opt}$ to be −1.46 dBm for RIN = −160 dB/Hz and −6.46 dBm for RIN = −150 dB/Hz.

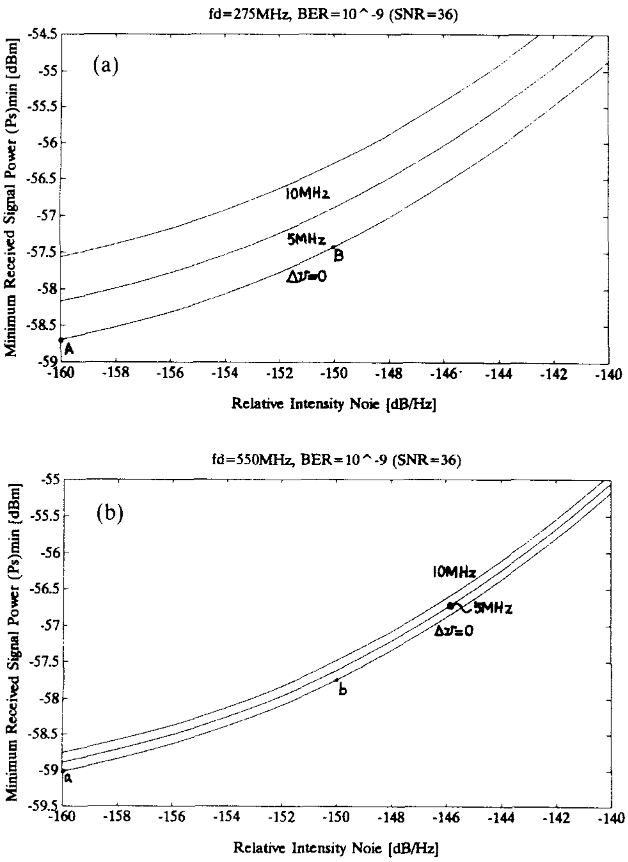

Figure 3 The minimum receiver signal power P_S as a function of RIN for (a) f_d = 275 MHz and (b) f_d = 550 MHz in terms of $\langle i_{th}^2 \rangle = 9 \times 10^{-24}$ A^2/Hz and $\Delta\nu$ = 0, 5 MHz, 10 MHz, respectively

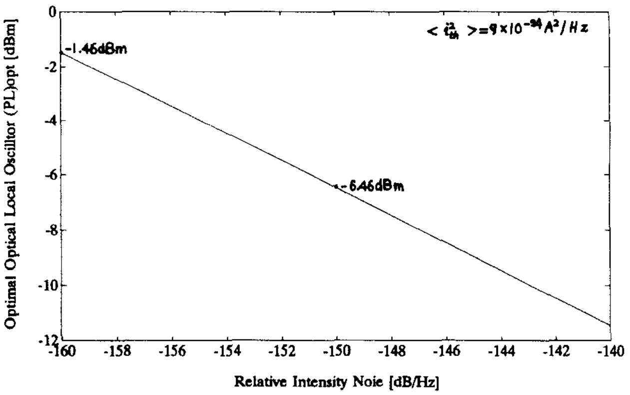

Figure 4 The optimal LO power (P_L) as a function of RIN for $\langle i_{th}^2 \rangle = 9 \times 10^{-24}$ A^2/Hz

CONCLUSION

The impact of local oscillator laser intensity noise on the performance of an optical phase-diversity FSK receiver using a delay-and-multiplying discriminator is investigated with the assumption of Gaussian noise distribution. Given the frequency deviation, data rate, laser linewidth, the RIN, and the thermal noise, we can analytically obtain the minimum received signal power together with the corresponding optimal local oscillator power for a specified BER at 10^{-9}.

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