Time-Domain Analysis of a Novel Phase-Locked Coherent Optical Demodulator

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Abstract: Detailed analysis of a novel highly linear phase-locked coherent optical demodulator is presented. We investigate how loop gain, phase-modulator non-linearity and amplitude modulation influence the Signal to Interference Ratio (SIR) of the demodulated signal.

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1. Introduction

Intensity modulated analog optical links have long been limited in performance by the nonlinear response of optical modulators [1]. The underlying reason for this is that the response of optical intensity modulators is ‘hard-limited’ by zero and full transmission. In contrast, optical phase modulation has no fundamental limit to modulation depth besides that given by the available modulation range in optical phase modulators. The challenge to implement a linear phase-modulated optical link lies in the receiver structure. A traditional coherent receiver has a sinusoidal response limiting the overall dynamic range of the optical link [2]. In this paper, we investigate a novel optical phase-locked receiver that overcomes the nonlinearity issue. By locking the local oscillator phase to a wide received optical phase modulation, the net signal-LO phase difference remains sufficiently small to fall within the linear range of the receiver. However, to achieve a high bandwidth phase-locked receiver, compact semiconductor phase modulators have to be used to keep loop delay sufficiently low. These modulators can have a nonlinear response, and therefore it is essential that the limitations from nonlinear phase or amplitude modulation are fully understood. However, by default, the linear loop approximation is not well suited to evaluate nonlinear loop behavior in a rigorous manner [3]. This is particularly true when several cascaded sources of nonlinearities are considered. In order to investigate these issues accurately, a time-domain model of the phase-locked demodulator is developed, which is in good agreement with initial experimental results [4].

2. Model set-up

The set-up of the phase-locked optical demodulator, on which we base our model, is shown in Figure 1.

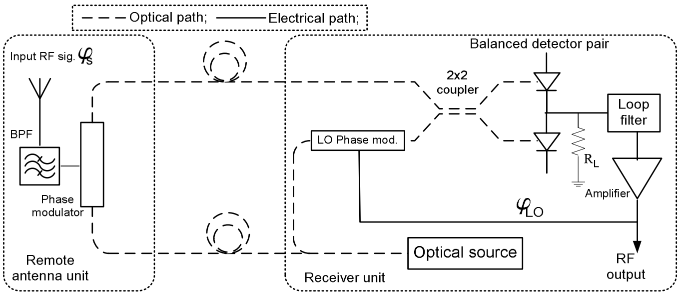

Fig. 1. General outline of phase modulated optical link and phase-locked optical demodulator at the receiver unit.

The received RF signal, φ_s, is used to directly modulate an optical phase modulator at the remote antenna unit. The optical signal is then transported to the receiver unit where the optical signal phase, φ_s, is compared to the reference phase (signal), φ_{LO}, using the balanced detector pair with load resistance R_L. The signal from the balanced detector pair, containing the phase difference between φ_s and $\varphi_{LO,}$ is then passed through the loop filter (low pass), amplified and applied to the LO phase-modulator. A single laser source is used for both the remote and the receiver unit. The desired demodulated signal is the electrical signal tapped before the LO phase-modulator. When the input RF signal consists of relatively closely spaced frequencies, the nonlinear response of the balanced detector, LO phase-modulator and residuals of amplitude modulation will result in intermodulation distortion of the demodulated signal. 3rd order intermodulation products are especially important because they may set the Spurious Free Dynamic Range (SFDR) of the system [2]. The demodulated signal is then characterized by the Signal-to-Intermodulation Ratio (SIR) which is the ratio between the power of the demodulated signal and 3rd order mixing product. Based on the model depicted in Figure 1, a set of non-linear differential equations describing the system are derived. The equations include the effects of the cascaded non-linearity of the phase detector, LO phase-modulator and residuals of the amplitude modulations. Loop gain is defined as: $K=\pi(P_sP_{LO})^{1/2}AR_{pd}R_L/V_\pi\tau_{LF}$, where P_s and P_{LO}: are powers of the optical signals at couplers input, A: gain of the amplifier, R_{pd}: responsivity of the photodiodes, R_L: load resistance and τ_{LF}: inversely proportional to the BW of loop filter. (V_π assumed equal for both modulators).

3. Effects of loop gain and phase-modulator nonlinearity

In Figure 2(a), Signal-to-Intermodulation Ratio (SIR) is computed as a function of the loop gain when the ratio between loop filter bandwidth and the RF input signal frequency, (f_{LF}/f^1_s), is varied. RF signal, φ_s, includes two closely spaced frequencies: f^1_s and f^2_s. The intermodulation is the magnitude of the mixing terms ($2f^1_s- f^2_s$, $2f^2_s- f^1_s$).

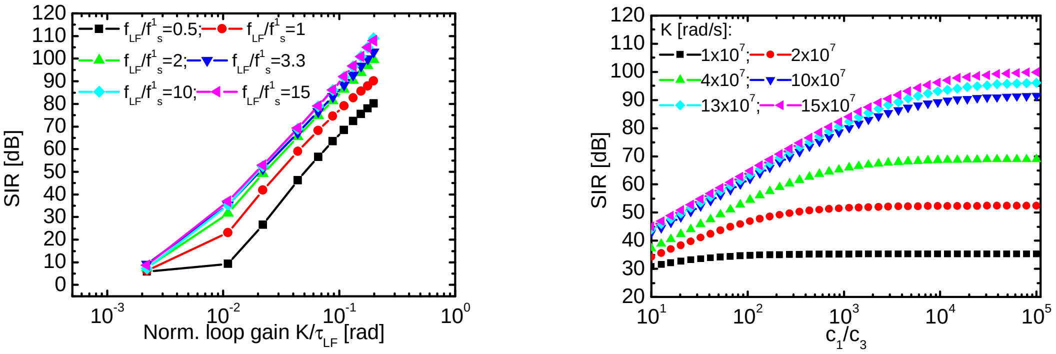

Fig. 2. RF input sig. modulation depth $M_{\varphi s}=\pi/2$. (a) SIR of the demodulated signal as a function of normalized loop gain for selected values of the ratio f_{bw}/f^1_s. (b) SIR of the demodulated signal as a function of the ratio c_1/c_3 of the LO phase-modulator. Quadr.. term: 0.

Figure 2(a) illustrates that as the ratio, (f_{bw}/ f^1_s), is increased, the performance of the phase-locked demodulator improves in terms of SIR, i.e. the SIR of the demodulated signal increases for the specific value of the loop gain. As the ratio, (f_{bw}/f^1_s), is significantly increased, the SIR converges. Furthermore, the slope of the SIR line is approximately 3. Fig. 2(a) can be used to determine the required value of the loop gain in order to obtain the specific values of SIR. One of the key challenges in creating a linear demodulator is the linearity of the tracking LO phase-modulator. The phase-change vs. voltage characteristic of the LO phase-modulator is nonlinear and thereby reducing the SIR of the demodulated signal. Usually, if the phase-modulator is operated in push-pull configuration, the even terms in a polynomial expansion of the phase-modulator response around the bias point can be cancelled. Thus, the cubic term is the one of most concern. In Figure 2(b), SIR is computed as the ratio between the linear term (c_1) and cubic term (c_3) of the LO phase- modulator response. In general, the SIR decreases as the ratio c_1/c_3 decreases. The values of c_1/c_3 for which SIR starts to decrease are loop gain dependent since the nonlinearities of the LO phase-modulator become more enhanced as the loop gain is increased. For the loop gain of $K=10\text{x}10^7$rad/s, the ratio c_1/c_3 needs to be $>10^4$, to maintain the SIR of 90 dB. Even though mixing terms from even-order nonlinear terms in the modulator response will have frequencies separated from a band-limited signal, the effect of cascaded nonlinear components will mirror these mixing terms back into the signal band. It is therefore necessary to investigate the effect of the quadratic term c_2. In Figure 3(a), SIR of the demodulated signal is computed as a function of the ratio c_1/c_3 for the selected values of c_1/c_2 ratio. The results in Figure 3(a) show that for non-zero values of c_2, there exist a combination of c_2 and c_3 for which the 3rd order mixing product is minimized, i.e. peaking (resonance) of the SIR. The resonance peak moves towards lower values of c_3 as c_2 is decreased. In the presence of quadratic nonlinearity c_2, the SIR curve approaches the case $c_2=0$ as c_3 is increased. In this case the SIR is limited by the cubic term of the LO phase-modulator response. For low values of c_3 the SIR is limited by the quadratic term, as shown in Figure 3(a). In Figure 3(b), the SIR is plotted as a function of the ratio c_1/c_3 when $c_1/c_2=300$, as the modulation depth $M_{\varphi s}$ of the input RF signal φ_s is varied. It is observed that the value of the ratio c_1/c_3 for which the resonance occurs remains approximately the same, only the level of the SIR is changed, i.e. as modulation depth increases SIR decreases as expected.

4. SIR degradation due to amplitude modulation

In addition to nonlinearities of the LO phase-modulator, any residual amplitude modulation, as would be expected in practice, may affect the performance of the demodulator in an adverse way. The normalized E-field amplitude of the LO signal can therefore be expressed as: $|E_{LO}|/A_0=1 + D_1\varphi_{LO}+D_2\varphi^2_{LO}+D_3\varphi^3_{LO}+\ldots$ where A_0 is the E-field amplitude of the LO signal in the absence of amplitude modulation. D_x (x=1,2,3…) represents the terms of the polynomial expansion of the amplitude modulated signal. In Figure 5, the SIR of the demodulated signal is comput-

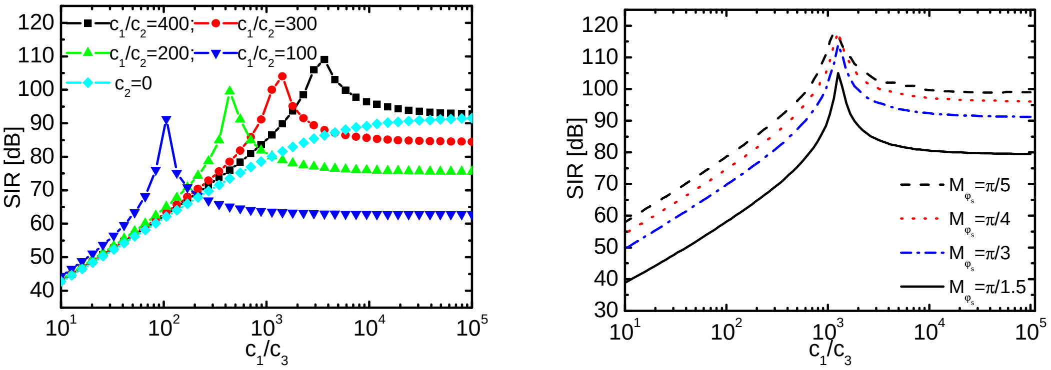

Fig. 3. (a) SIR of the demodulated signal as a function of c_1/c_3. The ratio c_1/c_2 takes values: 100, 200, 300, 400. (b) SIR of the demodulated signal as a function of c_1/c_3 for selected values of modulation depth $M_{\varphi s}$ of the input RF signal. c_1/c_2=300.

ed as a function of D_x where x=1,2 and 3. We assume that terms D_x where x>3 are negligible, as it would be expected in practice. Figure 4 shows that as D_1 (D_x=0 for x=2,3) is increased beyond $5x10^{-3}$ 1/V, the SIR starts to decrease. When D_2 is varied (D_x=0 for x=1, 3) resonant behavior of the SIR, similar to Figure 3(b), is observed, i.e. there exist a value of D_2 for which the 3rd order mixing product is minimized. We observe, Figure 4, that the effect of D_1 is more deteriorating than that of D_2. For the case when D_3 is varied (D_x=0 for x=1, 2), the SIR is not affected.

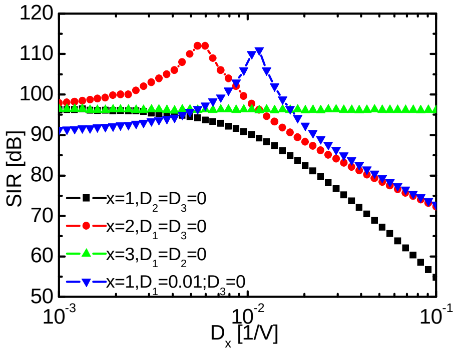

Fig. 4. SIR of the demodulated signal as a function of D_x for x=1,2,3. (c_2,c_3)=0.

When D_1=0.001 1/V and D_2 is varied, the SIR is degraded for low values of D_2 since the SIR is in this case limited by the linear term D_1. Furthermore, the shift in resonant peak towards higher values of D_2 is observed.

5. Conclusion

A detailed numerical model, including the system nonlinearities, of the novel phase-locked optical demodulator has been presented. LO Phase-Modulator (PM) nonlinearities severely limit the SIR of the demodulated signal. However, in the presence of quadratic LO PM nonlinearity, there exists a range of values of the ratio c_1/c_3 for which the SIR can be maximized. If the quadratic term is fully cancelled the cubic term of the LO PM should be app. < $5\cdot 10^{-4}$ in order to maintain high values (>90dB) of SIR. Only the linear and the quadratic term of the amplitude modulation limit the SIR.

6. Acknowledgments

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7. References

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