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Relative stability analysis of optical injection phase-locked loop

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ABSTRACT

In this paper, we analyze the relative stability of optical injection phase-locked loop (OIPLL) in terms of the phase margin considering loop-delay into account. Phase margin of first- and second-order OIPLL are calculated as a function of loop-delay, damping factor and other parameters of the loop. The effects of optical injection on damping factor and phase margin of the loop are shown. It is observed that the OIPLL has better stability than the conventional optical phase-locked loop (OPLL) in presence of loop-delay.

1. Introduction

The OIPLL technique combines both OPLL and OIL principles. The objective is to combine the benefits of both techniques and to complement their weaknesses. OIPLL is needed for many applications in RF and photonic systems such as generation of low noise microwave or mm-wave, timing stabilization of a mode locked laser, coherent combination of two mutually coupled heterodyne phase-locked laser beams, and PSK signal reception. In the last few years, lot of works has been carried out on OIPLL and in connection to its different applications [1–10]. OPLL has non-zero signal propagation time; therefore every loop is associated with finite time-delay. Loop propagation delay imposes a restriction on the higher value of the loop natural frequency due to the stability condition [11–13]. Also, tracking performance of the loop in terms of the phase-error variance even at the optimum condition rises sharply with the delay. Lower value of the loop natural frequency decreases the pull-in range, increases the pull-in time, increases tracking error, and increases the phase-error variance. We know that though there is limitation on the locking range of the injection synchronization yet it does not add loop-delay. Thus the solution is to combine the principle of injection synchronization and phase locking technique. The combination results in a system with low values of phase-error variance, (though not up to the desired value) over a much wider stable locking range. But detailed analysis shows that the effect of loop-delay, although minimized, still remains. It is known that wider the locking range, longer the mean time between cycle-slips in a tracking system. As a result, the restrictions imposed on the line-width of the lasers are relaxed and the use of commercially available DFB lasers in place of very expensive and bulky narrow line-width lasers is seen commercially viable. However, the need of a very low value of phase-error variance for the (semi) coherent reception of digital signals with the error probability of 10^{-9} is not fulfilled with this arrangement. It is easily appreciated from the above discussion that the addition of the injection synchronizations path effectively increases

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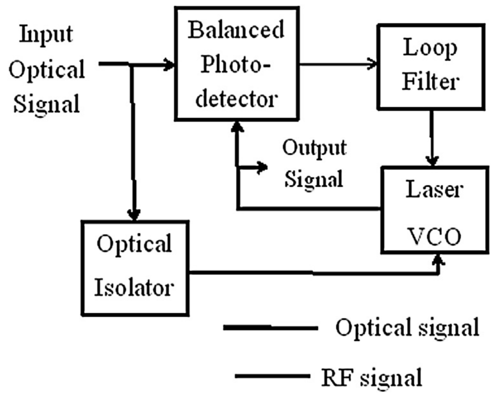

Fig. 1. Homodyne OIPLL schematic diagram.

the loop bandwidth. As a result the tracking system becomes more faithful in following phase variation of the input signal and because of the increase of the loop bandwidth noise rejection capability becomes weak. Thus it is highly important to examine the relative stability of OIPLL in the presence of loop-delay. In practice, it is desirable to operate OIPLL well within the stability region. In this respect, the so called phase margin is often used as a measure of degree of loop stability. But as far the knowledge of the author goes, no attempt has been made till now to quantify the phase margin of OIPLL in the presence of loop-delay. In this paper, an attempt has been made to throw light on various new aspects of relative stability of OIPLL and the influence of optical injection on the phase margin of the loop.

The rest of this paper is organized as follows. In Section 2, we present the governing equations of OIPLL system to describe the relative stability of the loop, while in Section 3 we calculate the damping factor of the loop in presence of optical injection. In Section 4, the phase margin of the first- and second-order OIPLL with two different loop filter configurations are calculated. Numerical results and discussion are shown in Section 5. Finally, Section 6 concludes this paper.

2. Governing equations of OIPLL

Let us consider the schematic structure of a homodyne OIPLL system shown in Fig. 1. It consists of a photo-detector, a loop filter, a slave laser and an isolator. The received and the phase modulated optical signals are combined by a 3-dB directional coupler, and the resulting optical signal is converted in the electrical domain by two balanced photodiodes. The diodes are interconnected so that, the signal difference between their photocurrents, drives the following loop filter. The balanced front end reduces loss by using both branches of the coupler, and it provides LO intensity noise suppression. The electrical signal at the balanced detector output is then processed by a standard loop filter, and finally sent to the VCO laser input. Instantaneous frequency of the VCO laser is controlled by two mechanisms, namely, through injection locking and optical phase-locked principle using an additional arrangement for controlling the output phase of the VCO laser in correspondence to a measure of the instantaneous phase-error. Locking is acquired when the two lasers oscillate at the same frequency. The electric fields of the incoming signal and the VCO light can be expressed, respectively, as

$$E_R(t) = \sqrt{P_R}\exp\left(j\left(\omega_R t + \phi_{nR}(t)\right)\right) \tag{1}$$

$$E_{L0}(t) = \sqrt{P_{L0}}\exp\left(j\left(\omega_{L0}t + \phi_{VCO}(t) + \phi_{INJ}(t) + \phi_{nLO}(t)\right)\right) \tag{2}$$

where PR is the received signal power (W), ωR is the angular frequency (rad/s) of the received signal and $\phi_{nR}(t)$is the phase noise of the transmitter laser source. In (2), PL0 is the LO laser power (W), ωLO is the angular frequency (rad/s) of the LO laser signal, $\phi_{nLO}(t)$is the phase noise of the LO laser source, $\phi_{VCO}(t)$ is phase modulation of the local laser VCO due to the input to the VCO and $\phi_{INJ}(t)$ is the phase modulation of the local laser VCO due to injection signal. For the present we assume that VCO's phase is in lock to the received signal phase, it can then be assumed that the phase-error $\phi_E(t) << 1$. Assuming a balanced photo-detector, it is easily shown that the photo-detector output is given by

$$V_\phi(t) = K_{PD}\phi_E(t) + n(t) \tag{3}$$

$$\text{where}\,\phi_E(t) = \left(\phi_{nR}(t) - \phi_{nLO}(t)\right) - \phi_{VCO}(t) - \phi_{INJ}(t) \tag{4}$$

is the total phase-error, $K_{PD} = 2RR_T\sqrt{P_R P_{L0}}$ is the phase detector gain, R is the photo-detector responsivity (A/W), RT is the trans-impedance (Ω) and $n(t)$ is the shot noise associated with the photo-detectors.

The control voltage at the output of the loop filter is given by

$$V_f(t) = V_\phi(t) * f(t) \tag{5}$$