Chapter-3

Modified Balanced Optical Phase-Locked Loop
— A Simulation Study

3.1 Introduction

Optical phase-locked loops (OPLL) are used in many applications involving frequency stabilization of a laser, clock extraction in high-speed optical communication systems, low noise microwave or mm-wave signal generation, and precise optical measurements. In the last few years, lot of works has been carried out on OPLL and in connection to its different applications. A balanced OPLL used for clock recovery at a bit rate of 160 Gbps was suggested and experimentally demonstrated [1]. Zibar et al. [2], analyzed a balanced OPLL used for clock extraction from high-speed optical time division multiplexed (OTDM) signals. The effects of loop-delay time and the laser transfer function were included in the differential equations describing the system, and a detailed timing jitter analysis was performed. A coherent receiver based on an OPLL for linear phase demodulation was presented [3]. For high-frequency operation, monolithic and hybrid integrated versions of the receiver were developed and experimentally verified in an analog link. Also, a novel phase-locked coherent optical phase demodulator with feedback and sampling was proposed and investigated for high-linearity microwave photonic links [4]. A novel coherent optical receiver based on an OPLL was presented and experimentally demonstrated to reduce the nonlinear distortion in a traditional receiver while retaining the signal to noise ratio (SNR). Up to 15-dB of spur free dynamic range (SFDR) improvement was obtained [5]. A high dynamic range phase modulated optical link using an attenuation-counter propagation photonic phase-locked loop (ACP-PPLL) was reported [6]. A modified OPLL that incorporated a frequency discriminator was proposed [7] to increase the frequency acquisition capability. Also, an OPLL incorporating a frequency down-conversion module was proposed and demonstrated [8]. The use of the frequency down-conversion module allows the use of lower-frequency components in the phase control module, which would reduce significantly the system
cost. A packaged semiconductor laser OPLL for photonic generation, processing and transmission of microwave signals was implemented [9]. Microwave carriers in the range of 7-14 GHz were generated with a phase-error variance of $7 \times 10^{-4}$ rad$^2$ in a 15-MHz bandwidth and 0.4 ns loop-delay condition. Also, a high purity mm-wave optical-beat signals at frequencies up to 330.566 GHz was generated [10].

OPLL has non-zero signal propagation time; therefore every loop is associated with finite time delay. The effect of loop-delay may not be visible in the amplitude response characteristics, yet it affects the phase response of the loop output. When the effect of loop-delay is taken into account two things happen. Firstly, it imposes a restriction on the higher value of the loop natural frequency due to the stability condition [11]. Secondly, the phase-error variance even at the optimum condition rises sharply with the delay. Lowering of the loop natural frequency has cascading effects on the loop performance, namely, it decreases the pull-in range, increases the pull-in time, increases tracking error, increases the phase-error variance etc. The loop propagation delay induces a phase delay at the output of the local oscillator (LO) VCO. This can be minimized by advancing the phase of the LO through an external control by means of a phase modulator [12], [13].

In order to be able to control the parameters viz., loop stability, frequency pulling time, and loop gain, a modified balanced OPLL having an additional arrangement for phase modulation is proposed in this chapter. The modified balanced OPLL is investigated through simulation experiment, considering the photodetectors shot noise and laser phase noise in presence of loop propagation delay. The analyses are made in terms of loop stability, the lock range, pull-in time and phase-error standard deviation (PESD) in presence of loop-delay time. The loop parameters are properly chosen for this simulation experiment.

3.2 System description

The modified balanced optical phase-locked loop is shown in Fig. 3.1. This modified loop contains all the components of a standard balanced OPLL in conjunction of an additional electro-optic phase modulator [14], [15]. 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 transimpedance amplifier. The transimpedance amplifier provides impedance matching. The balanced front end reduces loss by using both branches of the coupler, and it provides LO intensity noise suppression [16]. The electrical signal at the loop amplifier output is then processed by a standard first-order active filter, and finally sent to the VCO laser input. The electro-optic phase modulator is then used to modulate the phase of the optical signal at the VCO laser output. When OPLL is locked, the loop tracks the incoming signal frequency and phase.

**Fig. 3.1** Block schematic of (a) modified balanced optical phase-locked loop, and (b) balanced photodetector with transimpedance amplifier.
3.3 **Theoretical background**

In this section, we briefly describe the related theory of modified balanced optical phase-locked loop. Consider a modified balanced OPLL as shown in Fig. 3.1.

3.3.1 **Governing equations of the modified balanced optical phase-locked loop**

The received optical signal can be expressed as

\[ E_R(t) = \sqrt{P_R} \sin(\omega_R t + \phi_{nr}(t)) \]  \hspace{1cm} (3.1)

where \( P_R \) is the received signal power (W), \( \omega_R \) is the angular frequency (rad/s) of the received signal and \( \phi_{nr}(t) \) is the phase noise of the transmitter laser source.

The LO\(^1^*\) laser signal after phase modulation can be expressed as

\[ E_{LO}(t) = \sqrt{P_{LO}} \cos(\omega_{LO} t + \phi_{PM}(t) + \phi_{VCO}(t) + \phi_{nLO}(t)) \]  \hspace{1cm} (3.2)

where \( P_{LO} \) is the LO laser power (W), \( \omega_{LO} \) is the angular frequency (rad/s) of the LO laser signal and \( \phi_{nLO}(t) \) is the phase noise of the LO laser source. In (3.2), \( \phi_{VCO}(t) \) is phase modulation of the local laser VCO due to the input to the VCO terminal, and \( \phi_{PM}(t) \) is phase modulation of the local laser VCO due to the phase modulation of the phase modulator.

The optical coupler, being a symmetrical 180\(^\circ\)/3-dB device, generates the sum and difference of its input fields

\[ E_1 = \frac{1}{\sqrt{2}}(E_R + E_{LO}) \]  \hspace{1cm} (3.3A)

\[ E_2 = \frac{1}{\sqrt{2}}(E_R - E_{LO}). \]  \hspace{1cm} (3.3B)

\(^{1^*}\) Note that \( E_R \) and \( E_{LO} \) are 90\(^\circ\) out of phase with one another. The input has been written as a sine and the LO voltage has been written as a cosine. It is a typical multiplier-type phase detectors that the LO locks in quadrature to the incoming signal, so the notation is arranged in anticipation of this fact.
Illuminating the surface of a photodiode with an optical field $E$ will lead to a current of

$$i_{PD} = R|E|^2$$  \hspace{1cm} (3.4)

flowing through the diode. In (3.4), $R$ is the photodetector responsivity (A/W).

Using equations (3.1)-(3.4), the balanced photodetector output is expressed by

$$V_{\phi}(t) = K_{PD} \sin \phi_{E}(t) + n(t)$$  \hspace{1cm} (3.5)

where $\phi_{E}(t) = (\omega_R - \omega_{LO}) t - \phi_{PM}(t) - \phi_{VCO}(t) + (\phi_{nR}(t) - \phi_{nLO}(t))$ is the phase-error at the output of the detector and $n(t)$ is the shot noise associated with the photodetectors.

The expression

$$K_{PD} = 2RR_{T}\sqrt{P_k P_{L0}}$$  \hspace{1cm} (3.6)

is the phase detector gain (V/rad) of the OPLL, where $R_T$ is the transimpedance ($\Omega$).

Consider a standard first-order active loop filter with transfer function

$$F(s) = \frac{1 + s\tau_2}{s\tau_1},$$

where $\tau_1$ and $\tau_2$ are filter time constants. If its output is $V_f(t)$, then it is related to its input $V_{\phi}(t)$, by the following equation

$$\tau_1 \frac{dV_f(t)}{dt} = \tau_2 \frac{dV_{\phi}(t)}{dt} + V_{\phi}(t).$$  \hspace{1cm} (3.7)

Now, the different phase modulation components of the LO laser source are given by [17]

$$\phi_{VCO}(t) = K_{VCO} \int_{-\infty}^{t} V_f(t' - \tau)dt'$$  \hspace{1cm} (3.8)

$$\phi_{PM}(t) = K_{PM} V_f(t - \tau)$$  \hspace{1cm} (3.9)

where $K_{VCO}$ is the VCO laser sensitivity (rad/(s.V)), $K_{PM}$ is the phase modulator sensitivity (rad/V) and $\tau$ (second) is the loop propagation delay.

### 3.3.2 Noise in modified balanced optical phase-locked loop

Several noise sources affect the performance of the OPLL system. For homodyne OPLL the main noise sources are (a) phase fluctuations of the input signal, (b) phase fluctuation of the homodyne signal between the source laser and VCO laser, and (c)
additive noises like photodetector shot noise, intensity noise of the lasers. However, among these noise sources, only the photodetectors shot noise and laser phase noise are the practical limitations in balanced OPLL. The phase noise consists of three components, white frequency noise, flicker frequency noise, and random-walk frequency noise. Out of these, the white frequency noise significantly degrades the OPLL performance because the flicker frequency and random-walk frequency noise strength is negligible since the carrier frequency is very large (≈ THz). The power spectral density (PSD) of the phase noise due to the white frequency noise of laser is given by [18]

\[ S_{PN}(f) = \frac{\Delta\nu}{\pi f^2}, \quad 0 < f < \infty \]  

(3.10)

where \( S_{PN}(f) \) (rad²/Hz) is the one-sided PSD of the phase noise stemming from the white frequency noise, and \( \Delta\nu \) (Hz) is the full-width-half-maxima (FWHM) of the transmitter and VCO laser linewidth.

The power spectral density of the shot noise is represented by [19]

\[ S_{SN}(f) = 2qRR_T^2(P_R + P_{LO}), \quad 0 < f < \infty \]  

(3.11)

where \( S_{SN}(f) \) is the one-sided PSD (V²/Hz) of the shot noise and \( q \) is the electron charge (1.6×10⁻⁹ C).

### 3.4 Results and discussion

The proposed OPLL is numerically simulated in the MATLAB programming environment. In simulation experiment, the balanced OPLL is modeled considering strong nonlinearity of the loop and finite loop propagation delay. Both phase noise and shot noise are assumed to be White Gaussian noise. Polar Marsaglia method [20] is used to generate laser phase noise and photodetector shot noise. The loop-delay is introduced in the simulation programme as a delay to the error signal of the phase detector output to control the VCO laser frequency and is presented in Appendix-A. For the simulation study, the expression given by (3.7) can be re-written as

\[ V_f(t + \Delta t) = V_f(t) + \left[ \frac{\Delta t - \tau_2}{\tau_1} \right] V_\psi(t) + \frac{\tau_2}{\tau_1} V_\psi(t + \Delta t) \]  

(3.12)
where $\Delta t$ is the sampling interval. In (3.12), $V_f(t), V_f(t+\Delta t)$ are the loop filter output voltage at $t$-th and $(t+\Delta t)$-th instant of time, respectively and $V_\phi(t), V_\phi(t+\Delta t)$ are the balanced detector output at $t$-th and $(t+\Delta t)$-th instant of time, respectively. To obtain the value of $\phi_{vco}(t)$, the integration in (3.8) is done applying 4th order Runge-Kutta method [21]. In this procedure, $\phi_{vco}(t)$ is evaluated for each step of the calculation and the filter output controls the frequency and phase of the VCO, and slowly loop phase-lock is acquired.

The simulation results shown in this section are obtained by the time domain numerical model of the modified balanced OPLL. The numerical model of the modified OPLL is based on equations (3.1)-(3.12). It is important to mention that the operating frequencies of the lasers are very high (~ few hundred THz). Thus, for simulation study, large number of sampling points is required in time domain analysis. For this purpose, large number of computer memory is needed which is not available. To overcome this difficulty, the operating frequencies of the optical sources are scaled down to 100 kHz and so, laser linewidth is taken of the order of few kHz. The following (Table 3.1) typical numerical values [22]-[24] are used in our simulation.

### Table 3.1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Received Signal Power</td>
<td>$P_r = -53$ dBm</td>
</tr>
<tr>
<td>VCO Laser Power</td>
<td>$P_{lo} = 0.33$ dBm</td>
</tr>
<tr>
<td>Photodiode responsivity</td>
<td>$R = 1$ A/W</td>
</tr>
<tr>
<td>Transimpedance</td>
<td>$R_T = 2.74$ kΩ</td>
</tr>
<tr>
<td>VCO Sensitivity</td>
<td>$K_{vco} = 2\pi \times 300$ rad/(s.V)</td>
</tr>
</tbody>
</table>
3.4.1 Noise-free condition

In order to design the modified homodyne OPLL, commercially available DFB lasers (linewidth 2~20 MHz) can be used as the source laser and the local oscillator laser. Narrow linewidth laser sources are very expensive, and also they consume more power and are larger in size than DFB lasers. DFB lasers also have the advantage of potential optoelectronic integration. As DFB lasers linewidth ~ few MHz, loop propagation delay is non-negligible. The presence of this delay adds instability to the loop and manifests as a spurious locking. Frequency search halts and the loop appears to lock at a frequency that bears no obvious relation to the input frequency. Thus, it is highly important to examine loop stability. Here, we neglect all the noise components. Maximum allowable loop-delay variation with phase modulator sensitivity \( K_{PM} \) at absolutely zero phase-error condition is shown in Fig. 3.2. As seen in the figure, the maximum allowable loop-delay gradually increases as the phase modulator sensitivity increases. This means that the loop can accommodate larger value of the loop-delay without hampering the stable operating condition. Fig. 3.2 shows that as phase modulator sensitivity is increased beyond 12 rad/V [25], the maximum allowable loop-delay starts to decrease. So, maximum allowable value of \( K_{PM} \) should be of the order of 12 rad/V within stable boundary.

In optical coherent transmission systems, the most severe problem is the large fluctuation of the beat frequency of the optical sources. The pull-in limit should be as large as possible. To consider pull-in behavior, we neglect all the noise components including phase noise and we assume that the loop is operating in the unlocked mode, i.e., the incoming signal frequency is not equal to the VCO laser free-running signal frequency. The normalized phase detector output is plotted with time as presented in Fig. 3.3. From these figures it may be concluded that in Fig. 3.3(a) the loop acquires lock-in state after a few cycle slips than in Fig. 3.3(b), because in later case the system is delay limited with 20 ns loop-delay. Also, in Fig. 3.3(c), the lock-in condition reaches after a few number of cycle slips due to presence of phase modulator.
Lock-in range is an important parameter for judging the merit of an optical tracking system. Usually, lock-in range decreases with the increase of loop-delay. But in this modified homodyne loop, lock-in range increases with the electro-optic phase modulator sensitivity in the presence of loop-delay (Table 3.2). From this table, it is clear that about 31% increase in lock-in range (i.e. 11.20 MHz compared to 8.56 MHz) is possible with $K_{PM} = 12$ rad/V at 20 ns loop-delay condition.

**Table 3.2**

<table>
<thead>
<tr>
<th>Loop-delay (ns)</th>
<th>Lock-in Range for Conventional OPLL (MHz)</th>
<th>Lock-in Range for Modified OPLL (MHz) $K_{PM} = 12$ rad/V</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>50.20</td>
<td>62.10</td>
</tr>
<tr>
<td>10</td>
<td>10.15</td>
<td>11.68</td>
</tr>
<tr>
<td>20</td>
<td>08.56</td>
<td>11.20</td>
</tr>
</tbody>
</table>

**Fig. 3.2** Loop propagation delay as a function of phase modulator sensitivity. Simulation results are shown by the circles.
3.4.2 Noisy condition

In the simulation analysis, the phase-error standard deviation (PESD) is evaluated considering the laser phase noise and shot noise of the detector with finite loop-delay. At locked condition, the PESD is evaluated from the balanced phase detector output. Dependence of PESD on loop propagation delay is shown in Fig. 3.4, showing the effect of phase modulator control. The plots show that PESD increases with the increase of loop-delay. Consider PESD as 7°, the maximum loop-delay is increased from 1 ns to 7 ns with $K_{pm} = 12$ rad/V. Thus, in presence of phase modulator, the stability of the modified OPLL is enhanced and system can tolerate larger loop-delay.
Fig. 3.5 shows the phase-error standard deviation plotted against the sum of the linewidths of the transmitter and local oscillator lasers. It is observed that phase-error standard deviation increases with the increase of summed lasers linewidth. In presence of 10 ns loop-delay, the PESD reduces about 1.3° in presence of the phase modulator with sensitivity $K_{pm} = 12$ rad/V, at source laser linewidth $\left( \delta \nu_s \right) = 2.5$ MHz and local oscillator linewidth $\left( \delta \nu_{LO} \right) = 2.5$ MHz. As seen from the figure, phase modulator control is much pronounced for lasers with larger linewidth and considerable reduction of PESD can be achieved with external phase control. A frequently quoted value for the PESD required for binary phase-shift-keying (BPSK) signal is 10° [26], this being the value required for 0.5 dB power penalty at bit error rate (BER) of $10^{-10}$. Based on the above graph, this performance should be possible using DFB laser (linewidth ~ 2-20 MHz) in the presence of electro-optic phase modulator.

The effect of received signal power and VCO laser signal power are presented in Fig. 3.6 and Fig. 3.7, respectively. It is observed that PESD decreases with received signal power and VCO laser power almost linearly. Consider PESD as 7.5°, power requirement is relaxed for source laser from -48dBm to -51dBm and VCO laser from +5dBm to +2.1dBm with phase modulator sensitivity $K_{pm} = 12$ rad/V at 10 ns loop-delay condition. Thus, improvement in power sensitivity of source and local oscillator laser is 3 dBm and 2.9 dBm, respectively at same value of phase-error standard deviation, at source laser linewidth $\left( \delta \nu_s \right) = 2.5$ MHz and local oscillator linewidth $\left( \delta \nu_{LO} \right) = 2.5$ MHz. In presence of external phase control, the PESD reduces about 1° at optimum system performance.
**Fig. 3.4** Phase-error standard deviation versus loop propagation delay. Phase modulator sensitivity is used as a parameter. Simulation results are shown by the circles.

**Fig. 3.5** Phase-error standard deviation as a function of summed laser linewidth for 10 ns loop-delay. Phase modulator sensitivity is used as a parameter.
Fig. 3.6 Variation of phase-error standard deviation with transmitter laser power. Phase modulator sensitivity is used as a parameter. VCO laser power is +0.33 dBm. Simulation results are shown by the circles.

Fig. 3.7 Variation of phase-error standard deviation with VCO laser power. Phase modulator sensitivity is used as a parameter. Transmitter laser power is -53 dBm. Simulation results are shown by the circles.
3.5 Conclusion

A simulation study of a modified balanced OPLL has been performed taking into account photodector shot noise, laser phase noise and loop propagation delay. This modified OPLL contains all the components of a standard balanced OPLL in conjunction of an additional electro-optic phase modulator in the phase-locking branch. The additional phase modulator has been introduced at the output of the laser VCO to improve the tracking capability of the loop by providing the additional negative frequency feedback. It has been found that the proposed system accommodates larger loop-delay than the conventional OPLL without affecting the loop stability. With the phase modulator, the lock range increases in presence of loop-delay and also the loop acquisition time decreases. Thus, the loop achieves lock-in state in a relatively smaller time than the conventional loop. Considerable reduction in phase-error standard deviation has been observed by properly adjusting the phase control parameter and other parameters. In this modified loop, by adjusting the phase control parameter, the linewidth requirement can be easily increased to a large value without crossing the stability limit. So this modified OPLL is preferable for the optical sources having larger linewidth, i.e., commercially available DFB lasers (linewidth ~ 2-20 MHz). Another finding of the proposed OPLL is the improvement in power budget for laser sources for cost-effective OPLL system is promising one for future optical communication networks.
References


