Chapter 7 Conclusion

Most of the applications in the field of optics today utilize the intensity information of optical signals. The phase of an optical signal is at least equally, if not more, important than the intensity information. The tremendous potential of phase coherent optics is yet to be realized. OPLL provides a powerful tool to manipulate the phase of an optical signal. In this thesis I have studied OPLLs based on semiconductor lasers and the applications in coherent beam combining and coherence cloning. Looking into the future, significant amount of work needs to be done to bring this technology into practical applications.

First, similar to the PLL in electronic domain, OPLL is a technology platform that can enable numerous applications. Nevertheless, only a few applications based on OPLLs have been explored by researchers so far. The applications of this technology need to be significantly broadened by researchers to promote its further development.

Second, the performance of the OPLLs needs to be improved to bring them into practical applications. For OPLLs made from single section SCLs, the relatively small loop bandwidth(~MHz) limited by the phase reversal of the current-frequency modulation response presents the main obstacle toward achieving high performance OPLLs[22, 23, 36]. Firstly, the relatively small loop bandwidth combined with the large linewidth of SCLs leads to significant residual differential phase error between the master laser and the locked slave laser[10, 11, 91]. The smallest residual phase error I have shown in this thesis is about $0.1rad$, which is far from being useful for certain applications requiring very low residual phase noise such as coherent optical communication, RF signal generation and delivery etc. For coherent beam combining, the residual phase error can significantly reduce the combining efficiency and the combined beam quality. For coherence cloning, the small loop bandwidth limits the frequency range in which the frequency noise of the slave laser can be reduced. Secondly, the large frequency jitter and drift of SCLs due to temperature variations, current noise, and mechanical vibration, require additional compensation circuits to stably lock the lasers.

To solve the problem, one has to come up with a better laser design for flat frequency modulation response up to 1GHz. For example, one can make a laser of multiple sections and drive each section with modulation currents of different amplitudes and phases. Multi-section lasers have been designed with a reasonably flat FM response up to a few GHz[24]. However, their FM response depends on the bias current and is likely to change during aging[23].

Another approach to get around the problem is to add an external phase/frequency modulator in addition to the slave laser. The combined FM response of the laser plus the external phase/frequency modulator can be made flat by driving them separately. A similar concept has already been applied to lock fiber lasers by adding an acoustic optical modulator[21]. Modulation of fiber laser is typically realized with PZT fiber stretcher and the bandwidth is usually limited to a few kHz. The AOM acts as a frequency shifter and has much higher modulation speed. The loop bandwidth of the combined system can thus be enhanced but still limited to less than 1MHz because of the relatively long traveling time of the acoustic wave in the AOM. Using a similar idea, one can add a phase modulator in order to increase the loop bandwidth of the SCL OPLL.

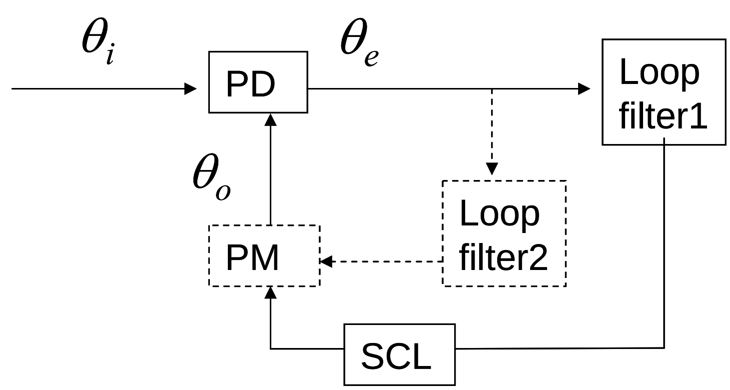

Fig. 7.1 Schematic diagram of an OPLL with a phase modulator (PM) feedback loop

Fig. 7.1 shows a schematic diagram of an OPLL with an additional phase modulator feedback loop. The solid lines and blocks stand for a typical OPLL built with a single-section SCL. In Chapter 2 I obtained the open loop transfer function of this OPLL as

$$G_{op}(s) = -\frac{K_{dc}F_1(s)H_{FM}^{DFB}(s)}{s}\exp(-s\tau_1) \tag{7.1}$$

where

$$H_{FM}^{DFB}(s) = -\frac{1}{1-a}\left(\frac{1}{1+\sqrt{s/2\pi f_c}} - a\right) \tag{7.2}$$

is the normalized FM response of the DFB laser. In Eq. (7.1), $s = j2\pi f$, and K_{dc}, $F_1(s)$, and τ_1 stand for the gain of the phase detector (PD), the transfer function of the loop filter 1 and the loop delay respectively. In Eq. (7.2) f_c is the structure-dependent thermal cut-off frequency of the slave laser and $a = K_{el}/K_{th}$ is the relative strength between the carrier effect and the thermal effect, and is typically smaller than 1.

Adding an external phase modulator following the DFB laser and using the same error signal to feed into the phase modulator as shown in Fig. 7.1, the OPLL contains two parallel feedback loops and the open loop transfer function is given by

$$G_{op}(s) = -\frac{K_d F_1(s)H_{FM}^{DFB}(s)}{s}\exp(-s\tau_1) + K_{PM}F_2(s)\exp(-s\tau_2) \tag{7.3}$$

where K_{PM}, $F_2(s)$, and τ_2 represent, respectively, the DC gain, the transfer function of the loop filter 2 and the delay of the PM feedback loop. In Eq. (7.3) I have assumed that the modulation strength of the phase modulator is almost constant within the frequency range (DC~ 1GHz) considered here. To simplify the analysis I first neglect all the loop delays and the loop filters. After substituting Eq. (7.2) into Eq. (7.3) one obtains

$$G_{op}(s) = \frac{K_{dc}}{s(1-a)}\left[-a + \frac{1}{1+\sqrt{s/2\pi f_c}}\right] + K_{PM} \tag{7.4}$$

The stability condition of the whole system requires $|G_{op}(s)| < 1$ at the π-phase frequency $\angle G_{op}(f_\pi) = -\pi$ [1]. Without the PM feedback loop, the thermal effect dominates at low frequency and gives way to the carrier effect at higher frequency. The shifting of the dominant effect causes $G_{op}(s)$ to experience a π phase reversal btween 100kHz-10MHz and thus limits the loop bandwidth to the same frequency range. By adding the phase modulator feedback loop one "adds" the term K_{PM} in Eq. (7.4). When sufficiently large, the combined thermal and PM contribution can dominate the carrier effect at all frequencies and the phase reversal of $G_{op}(s)$ is eliminated. Thus the constraint on the loop bandwidth is removed.

Considering the long loop delay, the complexity and cost of discrete fiber optical components, the best way to implement OPLLs is using planar integrated optics. Looking back on the history of electronic PLLs, it is the invention of PLL integrated circuits that had made the wide applications of PLL take off. Today, the technology of integrating SCLs, PDs, modulators and waveguides on the same chip is already available. Should OPLL chips of low cost and high performance be implemented, its extensive applications in phase coherent optics and RF photonics can be expected.