

Chapter 1 Introduction

1.1 Background and motivation

Phase locked loops(PLLs) are the most prolific feedback systems today and are widely used in almost all electronic systems including satellite communication systems, radars, cell phones, televisions, radios, pagers, computers, etc.[1, 2] The concept of PLL was first developed in the 1930's. The key parts in a PLL include a phase detector (PD) and a local oscillator whose frequency can be tuned by changing the input voltage or current. The system forces the local oscillator (LO) to follow the frequency/phase of an incoming reference signal. The earliest widespread use of PLLs was in radio and television. After the first PLL integrated circuit arrived in the 1960's, there has been an explosion of the use of PLLs in FM demodulation, synchronization, frequency synthesizers, etc.

Optical phase lock loops (OPLLs) are essentially the counterparts of PLLs in the optical domain, where a slave laser is used as the LO and is phase-locked to a master laser. The role of the phase detector is played by a photo detector. OPLL was first described four years after the invention of laser in 1960's[3]. Since then OPLLs based on various laser systems have been demonstrated[4-11]. One would naturally expect OPLLs to have a similar significance and impact in the optical domain as their counterparts have in the electronic domain. Historically, OPLLs have been studied for very few applications, including coherent optical communication[12-15], RF signal generation and delivery[4, 9-11], and most recently, in optical clocks[16-18]. Most of the OPLLs have been demonstrated in laboratories and have never achieved wide commercial application. The great potential of OPLL technology is far from being realized. This can be attributed to

both the very high cost, the immaturity of OPLL technology, and the lack of mature applications demanding this technology.

In an OPLL, the most critical condition to achieve the optical phase locking is that the sum of the linewidths of the master laser and the slave laser be much smaller than the loop bandwidth. This condition is relatively easy to implement with solid state lasers, gas lasers and fiber lasers because they have superior frequency stability and very narrow linewidth (equal or less than a few kHz), so they do not require a high loop bandwidth to be locked[11, 19]. However these lasers are very expensive and bulky. In addition, they are typically thermal or piezo tuned, which limits their tuning speed and range. These lasers have recently been used in very special applications, including space coherent optical communication[20], precision frequency standard synthesized using optical clocks[16-18], and accurate control of fiber lengths for millimeter wave signal distribution in large radio telescope arrays[21].

In comparison with solid state and fiber lasers, semiconductor laser (SCL) is a more favorable candidate to build agile, low cost OPLLs for a variety of applications, due to their unparalleled advantages:

- SCLs have a very high energy efficiency; state-of-the-art solid state lasers or fiber lasers have an efficiency of around 10%, while SCLs with efficiencies greater than 80% have been demonstrated recently.
- SCLs are significantly cheaper than solid state or fiber lasers.
- SCLs can be current tuned at very high speed.

- SCLs are very small. Due to their small size, the compatibility of their fabrication process with the semiconductor industry, and their current frequency tuning capability, SCLs are the excellent candidates to build integrated OPLL, which will significantly reduce their cost and open up numerous applications.

On the negative side, SCLs possess wide linewidth, which requires a high loop bandwidth and high speed feedback electronics to lock the lasers. A serious issue with single section SCLs is that their current frequency modulation(FM) response exhibits a 180° phase reversal within the frequency range of 0.1-10 MHz, which limits the loop bandwidth to the same frequency range[22, 23]. In order to efficiently lock the SCLs, either their linewidth has to be reduced, or the laser structure has to be redesigned to obtain a wide uniform FM response. In the late 1980's and early 1990's, a great deal of research activity was directed to the development of a coherent receiver for long-range coherent optical communication. Sub-MHz external cavity SCLs were built in laboratories and used to implement OPLLs [7, 9]. However, external cavity SCLs are complex, expensive, and bulky. Multi-section SCLs were demonstrated to possess a flat FM response up to a few GHz[11, 24]. However these lasers were only built in laboratories and had reliability issues[23]. In addition, coherent communication technology lost out to direct detection optical communication technology since the invention of Erbium doped fiber amplifiers in the 1990's. Research into SCL OPLLs has declined abruptly since then, except for some continuing work on RF signal generation with OPLLs[11].

In the last decade, the performance of SCLs has been improved significantly as a result of heavy investment in the telecom industry towards the end of the last century. Low cost telecom standard DFB lasers and external cavity SCLs with sub-MHz linewidth are now commercially available. The fact that their linewidth is smaller than the loop bandwidth limited by the thermal crossover makes it possible to lock these low cost, highly reliable commercial SCLs, and paves the way for a number of emerging applications. In this thesis I will study the OPLLs based on state-of-the-art commercial SCLs. In particular I will study the use of various high speed feedback electronics designs to improve the performance of SCL OPLLs, and explore the application of SCL OPLLs in coherent beam combining and coherence cloning.

Coherent beam combining(CBC) promises to enable high power laser systems with near-ideal beam quality for a number of industrial applications[25, 26]. Of the different CBC techniques, active feedback phase control is the most promising and has attracted intensive study[25, 27]. Conventionally, optical phase or frequency shifters such as phase modulators, fiber stretchers and acoustic optical modulators (AOM) are used in the feedback phase control system[25, 27-29]. Due to their ability to control the phase of the slave laser, OPLLs provide a natural platform for phase control of the SCLs, which enables a full electronic phase control system and significantly reduces the cost and dimension of the system by eliminating optical frequency/phase shifters.

Another application of OPLLs explored in this thesis is coherence cloning. For example, an optical sensing network requires a large number of coherent sources of very

narrow linewidths. Instead of using a number of solid state lasers or fiber lasers, an array of inexpensive SCLs can be locked to one high quality laser so that they have similar superior coherence properties. This technology can significantly reduce the system cost by eliminating the need for a large number of expensive solid state or fiber lasers. Another possible application is in the field of high precision optical clock signal distribution. Isolated high finesse optical cavities has been used to narrow a laser linewidth to less than Hz[30, 31]. One can easily transfer the superior frequency stability and coherence of this sophisticated laser system to SCLs by using heterodyne OPLLs.

1.2 Thesis outline

This thesis is organized as follows: The theoretical analysis of PLL in both the time and the frequency domain is presented in Chapter 2, with the latter one being the emphasis of this study. A major analysis tool called the bode plot, is introduced, and is used to study the performance of a PLL in terms of its stability, acquisition range, holding range, residual frequency noise, etc. I then add the non-uniform current FM response of the SCLs and the non-negligible loop delay into the analysis and consider their influence on the loop performance.

Chapter 3 is devoted to the experimental study of OPLLs. This chapter starts with the measurement of current FM response, and then presents the experimental demonstration and characterization of OPLLs based on various commercial SCLs. The last part of this chapter is devoted to the electronic filter design aimed at optimizing the system's performance. In particular, a phase lead-lag filter, passive and active lag-lead filters and an aided acquisition circuit are discussed and implemented.

An experimental study of coherent beam combining using OPLLs is presented in Chapter 4. I will first demonstrate the combination of two slave lasers phase locked to the

same master laser. However the optical path length variation in the combining fibers changes the combined output power and needs to be corrected for. A higher level PLL control loop using a RF voltage controlled oscillator (VCO) is introduced, analyzed, and implemented to correct for the optical path length variation in fiber. A combining efficiency of 94% is demonstrated.

Although I have demonstrated the coherent combining of two SCLs, the scalability of this technology to the combination of a large number of lasers is not clear. In Chapter 5, I will use a cascaded filled-aperture scheme to analyze the efficiency of combining a large number of lasers in the presence of various noise sources. In particular I will consider the residual differential phase error due to the limited loop bandwidth, the phase error introduced by the VCO phase control loop, the phase noise introduced by the high power fiber amplifiers in the MOPA scheme, the phase front error introduced by combining optics, and intensity noise.

In Chapter 6 I will present the study of coherence cloning using OPLLs. First I will present the theoretical description of the coherence property of a laser under both the free-running and the phase-locked conditions. I will then describe the measurement of the laser lineshape using a self-delayed heterodyne interferometer, and the measurement of frequency noise using a Mach Zehnder interferometer. Finally the measured linewidths and frequency noises of the master laser, the free-running and the phase-locked slave lasers are shown and compared.