Chapter 1

Overview

1.1 Introduction

The modulation of the intensity of optical waves has been extensively studied over the past few decades and forms the basis of almost all of the information applications of lasers to date. This is in contrast to the field of radio frequency (RF) electronics where the phase of the carrier wave plays a key role. Specifically, phase-locked loop (PLL) systems [1, 2] are the main enablers of many applications such as wireless communications, clock delivery, and clock recovery, and find use in most modern electronic appliances including cellphones, televisions, pagers, radios, etc.

The semiconductor laser (SCL) is the basic building block of most optical communication networks, and has a number of unique properties, such as its very large current-frequency sensitivity, fast response, small volume, very low cost, robustness, and compatibility with electronic circuits. This work focuses on utilizing these unique properties of an SCL not only to import to optics and optical communication many of the important applications of the RF field, but also to harness the wide bandwidth inherent to optical waves to enable a new generation of photonic and RF systems. We demonstrate novel uses of optoelectronic phase and frequency control in the fields of sensor networks, high power electronically steerable optical beams, arbitrary waveform synthesis, and wideband precisely controlled swept-frequency laser sources for three-dimensional imaging, chemical sensing and spectroscopy. Phase control is achieved using the current-frequency modulation property of the SCL in

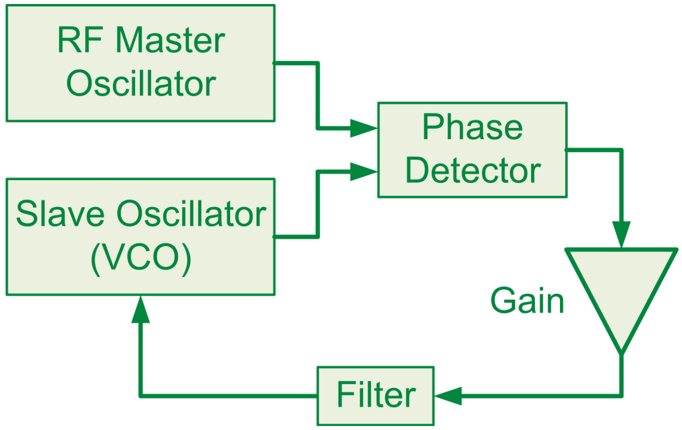

Figure 1.1. Schematic diagram of a generic phase-locked loop.

two optoelectronic feedback systems: the optical phase-locked loop (OPLL) and the optoelectronic swept-frequency laser (SFL).

1.2 Optical Phase-Locked Loops (OPLLs) and Applications

A PLL is a negative-feedback control system where the phase and frequency of a "slave" oscillator is made to track that of a reference or "master" oscillator. As shown in figure 1.1, a generic PLL has two important parts: a voltage-controlled oscillator (VCO), and a phase detector that compares the phases of the slave and master oscillators. The optical analogs of these electronic components are listed in table 1.1. A photodetector acts as a mixer since the photocurrent is proportional to the intensity of the incident optical signal; two optical fields incident on the detector result in a current that includes a term proportional to the product of the two fields. The SCL is a current-controlled oscillator (CCO) whose frequency is controlled via its injection current, thereby acting as the optical analog of an electronic VCO.

Ever since the first demonstration of a laser PLL [3] only five years after the first demonstration of the laser [4], OPLLs using a variety of lasers oscillators have been investigated by various researchers [5–24]. One of the basic requirements of an OPLL is that the summed linewidths of the master and slave lasers should be smaller than

Table 1.1. Comparison between electronic PLLs and OPLLs

	Electronic PLL	Optical PLL (OPLL)
Master oscillator	Electronic oscillator	High-quality laser
Slave oscillator	Voltage-controlled oscillator	Semiconductor laser (current-controlled oscillator)
Phase detector	Electronic mixer	Photodetector

the loop bandwidth, as shown in chapter 2. SCLs tend to have large linewidths (in the megahertz range) due to their small size and the linewidth broadening effect due to phase-amplitude coupling [25–28]. Therefore, OPLL demonstrations have typically been performed using specialized lasers such as solid-state lasers [5–9], gas lasers [10], external cavity lasers [11–16] or specialized multisection SCLs [17–23] which have narrow linewdths and desirable modulation properties. In this work, we explore OPLLs based on different commercially available SCLs, taking advantage of recent advances in laser fabrication that have led to the development of narrow-linewidth distributed feedback (DFB) and other types of SCLs. Further, we develop new phase-locking architectures that eliminate the need for specialized SCL design and enable the phase-locking of standard single-section DFB SCLs.

Research into OPLLs was mainly driven by interest in robust coherent optical communication links for long-distance communications in the 1980s and early 1990s, but the advent of the erbium doped fiber amplifier (EDFA) [29, 30] and difficulties in OPLL implementation made coherent modulation formats unattractive. Interest in OPLL research has been renewed recently, for specialized applications such as free-space and intersatellite optical communication links, extremely high bandwidth optical communication, clock distribution etc. It is no surprise, then, that the majority of OPLL research has focused on applications in phase-modulated coherent optical communication links [5, 6, 17, 18, 31–36], clock generation and transmission [14, 19, 37–39], synchronization and recovery [21, 40]. More recent work has investigated applications of OPLLs in intersatellite communications [9], optical frequency standards [41–43]

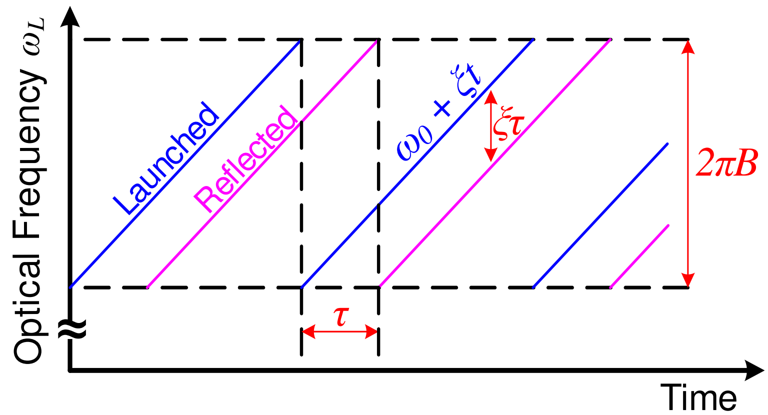

Figure 1.2. A frequency-modulated continuous wave (FMCW) experiment.

and phase-sensitive amplification [15, 44], to name a few.

In this work, we instead look at novel applications that focus on arrays of phase-locked lasers that form phase-controlled apertures with electronic control over the shape of the optical wavefront. We first show that the coherence properties of the master laser are "cloned" onto the slave laser, by direct measurements of the phase noise of the lasers in the frequency and time domains. This coherence cloning enables an array of lasers which effectively behaves as one coherent aperture, but with electronic control over the individual phases. We study applications of these phase-controlled apertures in coherent power-combining and electronic beam-steering.

1.3 Optoelectronic Swept-Frequency Lasers (SFLs)

Swept-frequency lasers have an important application in the field of three-dimensional (3-D) imaging, since axial distance can be encoded onto the frequency of the optical waveform. In particular, consider an imaging experiment with an SFL source whose frequency varies linearly with time, with a known slope ξ, as shown in figure 1.2. When the reflected signal with a total time delay τ is mixed with the SFL output, a beat term with frequency $\xi\tau$ is generated, and the time delay τ can by calculated by measuring the frequency of the beat note. This is the principle of frequency modulated continuous wave (FMCW) reflectometry, also known as optical frequency domain imaging (OFDI). Due to the method's high dynamic range and data acquisition that does not require high-speed electronics [45], FMCW reflectometry finds applications in light detection and ranging (LIDAR) [46–49] and in biomedical imaging [50, 51], where the experiment described above is known, for historical reasons, as swept source optical coherence tomography (SS-OCT). In fact, SS-OCT is now the preferred form of biomedical imaging using OCT, and represents the biggest potential application for SFL sources. Other applications include noncontact profilometry [52], biometrics [53], sensing and spectroscopy. The key metrics for an SFL are the total chirp (or "chirp bandwidth") B—the axial range resolution of the SFL is inversely proportional to B [54, 55]—and the chirp speed ξ, which determines the rate of image acquisition. It is desirable for the SFL to sweep rapidly across a very large bandwidth B.

State-of-the-art SFL sources for biomedical and other imaging applications are typically mechanically tuned external cavity lasers where a rotating grating tunes the lasing frequency [50, 56, 57]. Fourier-domain mode locking [58] and quasi-phase continuous tuning [59] have been developed to further improve the tuning speed and lasing properties of these sources. However, all these approaches suffer from complex mechanical embodiments that limit their speed, linearity, coherence, reliability and ease of use and manufacture. In this work, we develop a solid-state optoelectronic SFL source based on an SCL in a feedback loop. The starting frequency and slope of the optical chirp are locked to, and determined solely by, an electronic reference oscillator. By tuning this oscillator, we demonstrate the generation of arbitrary optical waveforms. The use of this precisely controlled optoelectronic SFL in a high-sensitivity label-free biomolecular sensing experiment is demonstrated.

While single-mode SCLs enable optoelectronic control and eliminate the need for mechanical tuning elements, they suffer from a serious drawback: their tuning range is limited to <1 THz. High resolution biomedical imaging applications require bandwidths of ≥10 THz to resolve features tens of microns in size. We therefore develop and demonstrate two techniques to increase the chirp bandwidth of SFLs, namely four-wave mixing (FWM) and algorithmic "stitching" or multiple source-(MS-) FMCW reflectometry. When the chirped output from an SFL is mixed with a monochromatic optical wave in a nonlinear medium, a new optical wave with twice the optical chirp is generated by the process of FWM. We show that this wave retains the chirp characteristics of the original chirped wave, and is therefore useful for imaging and sensing applications. As do all nonlinear distributed optical interactions, the efficiency of the above scheme suffers from lack of phase-matching. We develop a quasi-phase-matching technique to overcome this limitation. On the other hand, the MS-FMCW technique helps to generate high resolution images using distinct measurements taken using lasers that sweep over different regions of the optical spectrum, in an experiment similar to synthetic aperture radio imaging [60].

1.4 Organization of the Thesis

This thesis is organized as follows. SCL-OPLLs are described in chapter 2, including theoretical analyses and experimental characterizations. The limitations imposed by the FM response of a single-section SCL are described, and two techniques developed to overcome these limitations are described, viz. sideband locking [61] and composite OPLLs [62].

OPLL applications are described in chapters 3 and 4. The cloning of the coherence of the master laser in an OPLL onto the slave SCL [63] is thoroughly characterized, theoretically and experimentally, in chapter 3. Frequency domain (spectrum of the laser frequency noise) and time domain (Allan variance) measurements are performed and are shown to match theoretical predictions. The effect of coherence cloning on interferometric sensing experiments is analyzed. Applications of arrays of phase-locked SCLs are studied in chapter 4. These include coherent power-combining [64–67] and electronic beam-steering [68].

The optoelectronic SFL developed in this work [69] is described in chapter 5, and the generation of precisely controlled arbitrary swept-frequency waveforms is demonstrated. An application of the SFL to biomolecular sensing is studied. The extension of the bandwidth of swept-frequency waveforms for high resolution imaging applications is the focus of chapter 6. Two methods to achieve this: FWM [70] and MS-FMCW reflectometry [71] are analyzed and demonstrated.

A summary of the work and a number of possible directions to further develop this field are presented in chapter 7.