Chapter 7

Conclusion

7.1 Summary of the Thesis

We have shown that the use of an SCL as a current-controlled oscillator in optoelectronic feedback systems, making use of its direct (frequency vs. current) modulation property, enables precise electronic control of the laser phase and frequency. In particular, electronic control over the SCL phase is achieved using heterodyne OPLLs where a slave SCL is locked to a master laser offset by an RF reference oscillator; and SFL sources using SCLs in PLL-like feedback systems enable precise electronic control of the optical frequency chirp. The unique properties of the SCL such as its small footprint, low cost, high efficiency, robustness etc., and the optoelectronic systems which eliminate the need for any moving parts, precise mechanical alignment, or optical feedback and control, lead to a set of versatile and powerful devices which are attractive for use in many existing and novel applications.

Typical single-section SCLs, studied in this work, are characterized by a nonuniform FM response at low (<10 MHz) frequencies. We have theoretically analyzed the performance of SCL-OPLLs in the presence of this FM response, and a loop propagation delay; and experimentally demonstrated OPLLs using different commercial SCLs and optimized loop filters. The linewidth and FM response of an SCL determine the stability of an OPLL, and many lasers with larger linewidths ($\gtrsim$1 MHz) cannot be stably locked. To overcome this limitation, we have developed and demonstrated two novel OPLL architectures, viz. (i) the sideband-locked SCL-OPLL, where the feedback into the SCL was shifted to a higher frequency range where the FM response is uniform, and (ii) composite SCL-OPLL systems, where an external optical phase modulator was used to remove excess phase noise and stabilize the system.

Whereas SCL-OPLLs are typically studied for use as coherent demodulators in optical communication links, we have explored in this work other novel applications of SCL-OPLLs. We have shown theoretically and experimentally, in both the time and frequency domains, that the slave laser inherits the coherence properties of the master; this property is referred to as "coherence cloning." Coherence cloning of a master laser onto an array of slave SCLs, all locked to the same master laser, therefore forms a coherent aperture. We have demonstrated that the optical phase of each emitter in the array could be controlled in a one-to-one manner by varying the phase of an electronic oscillator in the OPLL, thereby forming a phase-controlled aperture with electronic wavefront control. Applications of these phase-controlled apertures in coherent power-combining and all-electronic beam-steering were studied.

We have designed and developed an optoelectronic SFL source based on a modification of the basic OPLL structure, by incorporating an MZI as a frequency discriminator. The output of the SCL was passed through the MZI and phase-locked to an electronic oscillator, to generate an optical wave whose frequency was swept ("chirped") precisely linearly and rapidly over a broad bandwidth (several 100 GHz in 0.1 ms). An iterative predistortion technique was also developed to overcome large nonlinearities in the laser's frequency vs. current tuning curve. The parameters of the frequency chirp were determined solely by the reference oscillator, and arbitrary optical waveforms were generated by tuning the electronic reference oscillator. The precise control over the optical frequency enabled high-sensitivity label-free biomolecular sensing experiments using a high-quality whispering-gallery-mode microresonator.

One of the most widespread use of broadband SFLs is in laser ranging and three-dimensional imaging. The axial resolution in these applications is inversely proportional to the chirp bandwidth, and very large chirp bandwidths ($\gtrsim$10 THz) are necessary for biomedical imaging (OCT). The tuning range of typical single-mode SCLs is, however, limited (typically $<$1 THz). We have demonstrated that FWM between the chirped SFL output and a monochromatic wave generates a chirped wave with twice the chirp bandwidth and the same chirp characteristics. We have also proposed and implemented a quasi-phase-matching scheme to overcome the effects of dispersion in the nonlinear medium. While bandwidth multiplication by FWM is a "physical" effect, we have also developed an algorithmic approach to achieve a larger effective bandwidth for imaging, by "stitching" measurements taken using SFLs chirping over different regions of the optical spectrum, in an experiment analogous to synthetic aperture radar. Using three separate SFL measurements, we have experimentally demonstrated a threefold improvement in the resolution using three SFL measurements.

7.2 Outlook

We have described a set of new optoelectronic devices for the manipulation of the phase and frequency, as opposed to just the intensity, of optical waves. For the most part, we have concentrated on experimentally constructing devices based on discrete, commercially available optical and electronic components. While these are adequate for many applications and for proof-of-principle demonstrations, the major step necessary to harness the full power of these devices is photonic and optoelectronic integration. If the limitations imposed by the SCL FM response are overcome, the minimization of the propagation delay will enable OPLLs with large loop bandwidths to be constructed. OPLLs based on micro-optics have already demonstrated [20] and recent efforts toward integrated OPLLs [22, 23, 77] are beginning to make progress in this direction. Development of integrated OPLLs will be necessary for large-scale integration of OPLL arrays for phase-controlled apertures for free-space optical communication, LIDAR and other applications; however, research into thermal stabilization and prevention of crosstalk in large laser arrays is expected to be necessary to make this a reality.

Integration of optoelectronic SFLs is also an important direction of research: the reduction of the footprint of these devices can enable integration with microresonators

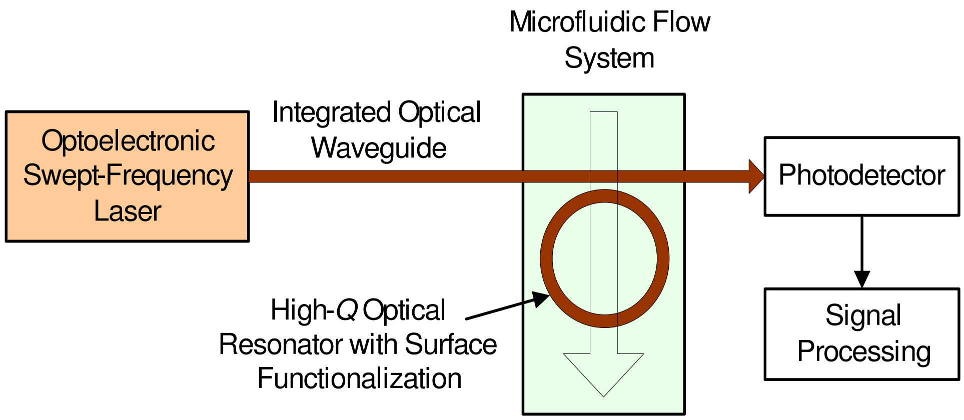

Figure 7.1. Schematic diagram of a potential compact integrated label-free biomolecular sensor. An optoelectronic SFL is coupled to a lithographically defined high-Q resonator with a functionalized surface for biomolecular detection. A microfluidic flow system enables delivery of a small volume of the analyte.

fabricated on chip to yield compact biomolecular sensing platforms (figure 7.1). Integrated optical waveguides on silicon are conducive to chirp multiplication by FWM, since they can have nonlinear coefficients that are up to five orders of magnitude larger than standard single-mode optical fibers [130]. Further, integration of SFLs into optoelectronic circuits enables the stitching of a large number of SFLs for high-resolution imaging (figure 6.18).

OPLLs and wideband SFLs have potential applications in the fields of millimeter-wave and Terahertz photonics. The use of OPLLs for generation and transmission of radio frequency of signals has been studied by various workers [39, 131]. With the development of high speed photodetectors and photomixers that can produce heterodyne output signals in the Terahertz regime [132], the frequency control methods developed in this thesis can be adapted for versatile and wideband Terahertz sources. By photomixing an optoelectronic SFL with a monochromatic laser source, it is possible to generate a narrow-linewidth and tunable "universal" Terahertz source. As faster and faster photomixers are developed, this represents a very promising field of research.

We have demonstrated the coherent combining of phase-locked optical sources for high-power sources. This concept can readily be extended to related fields to achieve improved performance. For example, the output powers of Terahertz photomixers and high-speed photodetectors are typically limited by optical damage thresholds in the small devices (a necessity for high-speed operation). This limitation can possibly be overcome by the coherent combining of the outputs of a number of terahertz detectors illuminated by phase-coherent optical sources. A second application is in the field of high power fiber amplifiers, where the output powers are limited by nonlinear effects in the optical fiber, mainly stimulated Brillouin scattering. It is known that modulating the phase or frequency of the optical wave results in a larger threshold for stimulated Brillouin scattering [133]—this suggests that the use of the optoelectronic SFLs developed in this work as seed sources for an array of high-power fiber amplifiers, and the subsequent coherent combining of the amplified outputs can result in larger output powers than the use of monochromatic seed lasers. Finally, the combining of the outputs of an array of N phase-locked SCLs, where each SCL (k) is locked to its preceding SCL ($k-1$) at a common RF offset frequency, can generate a comb of optical frequencies with independent control over the amplitude and phase of each frequency component. This *synthesis* approach is fundamentally different from the traditional top-down approach where individual components of a mode-locked laser and filtered and manipulated [134].

In summary, electronic control of the optical phase and frequency can be expected to enable a range of new applications, and vastly-improved performance in existing applications.