Chapter 1

Overview and Thesis Organization

1.1 Introduction

This thesis focuses on the construction and applications of the optoelectronic swept-frequency laser (SFL)—a feedback system that enables closed-loop control over the instantaneous optical frequency of a chirped semiconductor laser (SCL) [1–3]. Even though our feedback architecture is laser-agnostic, we restrict our attention to SCL diodes because of their small size, high wall-plug efficiency, and superior sub-MHz linewidths. The wide gain bandwidth of semiconductor quantum wells, the ability to fabricate SCLs with precisely controlled emission frequencies [4], and the fact that SCLs can be frequency tuned with current [5] enable broadband and agile coverage of the optical spectrum. These properties uniquely position the SCL as the device of choice for a range of high-fidelity applications, such as optical phase-locking and coherent combining [6–12], ranging and 3-D imaging [1, 13, 14], and spectroscopy and chemical sensing [6, 15]. The design and construction of the optoelectronic SFL is discussed in chapter 3.

The optoelectronic SFL can be configured to generate chirps with any arbitrary optical frequency vs. time profile, subject to the tunability of the SCL in its core. Precisely linear frequency sweeps are of particular interest because of their applications in optical frequency-modulated continuous-wave (FMCW) reflectometry and 3-D imaging, as described in chapter 2, and chirped-seed phase-locking, as described in chapter 6. Building on our group's expertise in the field of phase and frequency control of SCLs, we develop applications that take advantage of the unique properties of the SCL-based optoelectronic SFL. These applications can be subdivided into two categories: ranging and 3-D imaging using FMCW reflectometry, and coherent beam combining (CBC) of chirped-seed amplifiers (CSAs).

1.2 Ranging and 3-D Imaging Applications

The fundamental challenge of 3-D imaging is ranging—the retrieval of depth information from a scene or a sample. One way to construct a 3-D imaging system is to launch a laser beam along a particular axis, and collect the reflected light, in an effort to determine the depths of all the scatterers encountered by the beam as it propagates. A 3-D image may then be recorded by scanning the beam over the entire object space.

A conceptually simple way to retrieve depth information is to launch optical pulses, and record arrival times of the reflections. Scatterer depth can then be calculated by multiplying the arrival times by the speed of light c. Implementations based on this idea, collectively known as time-of-flight (TOF) systems, have been successfully demonstrated [16, 17]. The depth resolution, also called range resolution or axial resolution, of TOF methods depends on the system detection bandwidth, with 1 GHz yielding a resolution of $\Delta z \propto c \times (1 \text{ ns}) = 30$ cm in free space. Improvement of the resolution to the sub-mm range requires detectors with 100s of GHz of bandwidth, and is prohibitively expensive with current technology.

1.2.1 Optical FMCW Reflectometry

The technique of frequency-modulated continuous-wave (FMCW) reflectometry, originally developed for radio detection and ranging (radar), can be applied to the optical domain to circumvent the detector bandwidth limit by using a swept-frequency optical waveform. Systems utilizing FMCW reflectometry, also known as swept-source optical coherence tomography (SS-OCT) in the biomedical optics community, are capable of resolutions of a few μm with low detection bandwidths. As a result, FMCW reflectometry has found numerous applications, e.g. light detection and ranging (lidar) [18,19], biomedical imaging [20, 21], non-contact profilometry [22, 23] and biometrics [24, 25].

The FMCW technique is analyzed in full detail in chapter 2, and in chapter 3 we apply the optoelectronic SFL to FMCW imaging and demonstrate a simple profilometry application.

1.2.2 Multiple Source FMCW Reflectometry

In chapter 4 we describe multiple source FMCW (MS-FMCW) reflectometry—a novel imaging approach aimed at increasing the effective bandwidth of an FMCW ranging system. This is achieved by combining, or stitching, separate swept-frequency lasers (SFLs), to approximate a swept-source with an enhanced bandwidth [13,14,19]. The result is an improvement in the range resolution proportional to the increase in the swept-frequency range. This technique is of particular interest in the context of the SCL-based optoelectronic SFL. MS-FMCW leverages narrow SCL linewidths to present a pathway towards long-distance ranging systems with sub-100 μm resolutions.

1.2.3 The Tomographic Imaging Camera

FMCW reflectometry enables the retrieval of depth information from a single location in the transverse plane. One way to acquire a full 3-D data set is through mechanical raster-scanning of the laser beam across the object space. The acquisition time in such systems is ultimately limited by the scan speed, and for very high resolution datasets ($>$ 1 transverse mega pixel) is prohibitively slow. Rapid 3-D imaging is of crucial importance in *in vivo* biomedical diagnostics [21, 26] because it reduces artifacts introduced by patient motion. In addition, a high-throughput, non-destructive 3-D imaging technology is necessary to meet the requirements of several new industrial developments, including 3-D printing and manufacturing [27], 3-D tissue engineering [28–30], and 3-D cell cultures and tissue models [31].

In chapter 5 we discuss the tomographic imaging camera (TomICam), which combines FMCW ranging with non-mechanical transverse imaging, enabling robust, large field of view, and rapid 3-D imaging. We also discuss the application of compressive sensing (CS) to the TomICam platform. CS is an acquisition methodology that takes advantage of signal structure to compress and sample the information in a single step. It is of particular interest in applications involving large data sets, such as 3-D imaging, because compression reduces the volume of information that is recorded by the sensor, effectively speeding up the measurement.

1.3 Phase-Locking and Coherent Combining of Chirped Optical Waves

In chapter 6, we switch gears and discuss our work on the phase-locking of and coherent combining of chirped optical waves. The phase-locking of optical waves with arbitrary frequency chirps is a difficult problem in general. However, precisely linear chirps, such as the ones generated by the optoelectronic SFL can be phase-locked with very high efficiency using a frequency shifter. The main application of this result is the simultaneous stimulated Brillouin scattering (SBS) suppression and coherent combining of high-power fiber amplifiers.

The output power of optical fiber amplifiers is usually limited by SBS. Conventional methods to suppress SBS by increasing its threshold include the broadening of the seed laser linewidth through high-speed phase modulation. The increase in the amplifier SBS threshold comes at the expense of the seed coherence length [32], which places strict path-length matching requirements on the scaling of optical power through coherent combining of multiple amplifiers. Efficient coherent combining of such amplifiers has been demonstrated, but requires careful path-length matching to submillimeter accuracy [33, 34].

In chapter 6 we explore an architecture capable of SBS suppression and coherent combining without stringent mechanical path-length matching requirements. Our approach is to use the optoelectronic SFL as the amplifier seed, in order to reduce the effective length over which SBS occurs [35, 36]. We develop a chirped phase-locking technique and demonstrate its use in coherent beam combining of multiple chirped-seed amplifiers. Path-length matching requirements are relaxed due to the long coherence length (10s of meters) of semiconductor laser based SFLs.

The work described in chapter 6 was performed in collaboration with Jeffrey O. White's group at the United States Army Research Laboratory.