Optoelectronic Control of the Phase and Frequency of Semiconductor Lasers

Thesis by

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In loving memory of Dilip

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Abstract

This thesis explores the precise control of the phase and frequency of the output of semiconductor lasers (SCLs), which are the basic building blocks of most modern optical communication networks. Phase and frequency control is achieved by purely electronic means, using SCLs in optoelectronic feedback systems, such as optical phase-locked loops (OPLLs) and optoelectronic swept-frequency laser (SFL) sources. Architectures and applications of these systems are studied.

OPLLs with single-section SCLs have limited bandwidths due to the nonuniform SCL frequency modulation (FM) response. To overcome this limitation, two novel OPLL architectures are designed and demonstrated, viz. (i) the sideband-locked OPLL, where the feedback into the SCL is shifted to a frequency range where the FM response is uniform, and (ii) composite OPLL systems, where an external optical phase modulator corrects excess phase noise. It is shown, theoretically and experimentally, and in the time and frequency domains, that the coherence of the master laser is "cloned" onto the slave SCL in an OPLL. An array of SCLs, phase-locked to a common master, therefore forms a coherent aperture, where the phase of each emitter is electronically controlled by the OPLL. Applications of phase-controlled apertures in coherent power-combining and all-electronic beam-steering are demonstrated.

An optoelectronic SFL source that generates precisely linear, broadband, and rapid frequency chirps (several 100 GHz in 0.1 ms) is developed and demonstrated using a novel OPLL-like feedback system, where the frequency chirp characteristics are determined solely by a reference electronic oscillator. Results from high-sensitivity biomolecular sensing experiments utilizing the precise frequency control are reported. Techniques are developed to increase the tuning range of SFLs, which is the primary requirement in high-resolution three-dimensional imaging applications. These include (i) the synthesis of a larger effective bandwidth for imaging by "stitching" measurements taken using SFLs chirping over different regions of the optical spectrum; and (ii) the generation of a chirped wave with twice the chirp bandwidth and the same chirp characteristics by nonlinear four-wave mixing of the SFL output and a reference monochromatic wave. A quasi-phase-matching scheme to overcome dispersion in the nonlinear medium is described and implemented.

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Glossary of Acronyms

CBC Coherent beam-combining

CCO Current-controlled oscillator

DFB Distributed feedback

EDFA Erbium-doped fiber amplifier

FM Frequency modulation

FMCW Frequency modulated continuous wave

FWHM Full width at half maximum

FWM Four-wave mixing

GVD Group velocity dispersion

HNLF Highly nonlinear fiber

LIDAR Light detection and ranging

MOPA Master oscillator power amplifier

MS-FMCW Multiple source-frequency modulated continuous wave

MZI Mach-Zehnder interferometer

OCT Optical coherence tomography

OPLL Optical phase-locked loop

PD Photodetector

PLL Phase-locked loop

RIN Relative intensity noise

RF Radio frequency

SCL Semiconductor laser

SFL Swept-frequency laser

SS-OCT Swept source-optical coherence tomography

VCO Voltage-controlled oscillator

VCSEL Vertical cavity surface-emitting laser

VECSEL Vertical external cavity surface-emitting laser