The Optoelectronic Swept-Frequency Laser and Its Applications in Ranging, Three-Dimensional Imaging, and Coherent Beam Combining of Chirped-Seed Amplifiers

Thesis by

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Abstract

This thesis explores the design, construction, and applications of the optoelectronic swept-frequency laser (SFL). The optoelectronic SFL is a feedback loop designed around a swept-frequency (chirped) semiconductor laser (SCL) to control its instantaneous optical frequency, such that the chirp characteristics are determined solely by a reference electronic oscillator. The resultant system generates precisely controlled optical frequency sweeps. In particular, we focus on linear chirps because of their numerous applications. We demonstrate optoelectronic SFLs based on vertical-cavity surface-emitting lasers (VCSELs) and distributed-feedback lasers (DFBs) at wavelengths of 1550 nm and 1060 nm. We develop an iterative bias current predistortion procedure that enables SFL operation at very high chirp rates, up to 10^{16} Hz/sec. We describe commercialization efforts and implementation of the predistortion algorithm in a stand-alone embedded environment, undertaken as part of our collaboration with Telaris, Inc. We demonstrate frequency-modulated continuous-wave (FMCW) ranging and three-dimensional (3-D) imaging using a 1550 nm optoelectronic SFL.

We develop the technique of multiple source FMCW (MS-FMCW) reflectometry, in which the frequency sweeps of multiple SFLs are "stitched" together in order to increase the optical bandwidth, and hence improve the axial resolution, of an FMCW ranging measurement. We demonstrate computer-aided stitching of DFB and VCSEL sweeps at 1550 nm. We also develop and demonstrate hardware stitching, which enables MS-FMCW ranging without additional signal processing. The culmination of this work is the hardware stitching of four VCSELs at 1550 nm for a total optical bandwidth of 2 THz, and a free-space axial resolution of 75 μm.

We describe our work on the tomographic imaging camera (TomICam), a 3-D imaging system based on FMCW ranging that features non-mechanical acquisition of transverse pixels. Our approach uses a combination of electronically tuned optical sources and low-cost full-field detector arrays, completely eliminating the need for moving parts traditionally employed in 3-D imaging. We describe the basic TomICam principle, and demonstrate single-pixel TomICam ranging in a proof-of-concept experiment. We also discuss the application of compressive sensing (CS) to the TomICam platform, and perform a series of numerical simulations. These simulations show that tenfold compression is feasible in CS TomICam, which effectively improves the volume acquisition speed by a factor ten.

We develop chirped-wave phase-locking techniques, and apply them to coherent beam combining (CBC) of chirped-seed amplifiers (CSAs) in a master oscillator power amplifier configuration. The precise chirp linearity of the optoelectronic SFL enables non-mechanical compensation of optical delays using acousto-optic frequency shifters, and its high chirp rate simultaneously increases the stimulated Brillouin scattering (SBS) threshold of the active fiber. We characterize a 1550 nm chirped-seed amplifier coherent-combining system. We use a chirp rate of 5×10^{14} Hz/sec to increase the amplifier SBS threshold threefold, when compared to a single-frequency seed. We demonstrate efficient phase-locking and electronic beam steering of two 3 W erbium-doped fiber amplifier channels, achieving temporal phase noise levels corresponding to interferometric fringe visibilities exceeding 98%.

Contents

List of Figures

List of Tables

Glossary of Acronyms

2-D two-dimensional

3-D three-dimensional

AOFS acousto-optic frequency shifter

CBC coherent beam combining

CHDL chirped diode laser

CS compressive sensing

CSA chirped-seed amplifier

DDS direct digital synthesis

DFB distributed-feedback laser

EDFA erbium-doped fiber amplifier

FDML Fourier-domain mode-locked

FM frequency modulation

FMCW frequency-modulated continuous-wave

FSR free spectral range

FT Fourier transform

FWHM full width at half maximum

GRIN gradient-index

I/Q in-phase and quadrature

lidar light detection and ranging

MEMS microelectromechanical

MOPA master oscillator power amplifier

MS-FMCW multiple source FMCW

MZI Mach-Zehnder interferometer

OPLL optical phase-locked loop

PCB printed circuit board

PD photodetector

PLL phase-locked loop

PSD power spectral density

PSF point spread function

radar radio detection and ranging

RF radio frequency

RIN relative intensity noise

SBS stimulated Brillouin scattering

SCL semiconductor laser

SER signal-to-error ratio

SFL swept-frequency laser

SNR signal-to-noise ratio

SOA semiconductor optical amplifier

SS-OCT swept-source optical coherence tomography

TOF time-of-flight

TomICam tomographic imaging camera

VCO voltage-controlled oscillator

VCSEL vertical-cavity surface-emitting laser

VOA variable optical attenuator