Development of a FMCW LADAR Source Chip Using MEMS-Electronic-Photonic Heterogeneous Integration

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Abstract: We present recent advances in the development of an integrated Frequency Modulated Continuous Wave (FMCW) Laser Detection and Ranging (LADAR) source, demonstrating the capabilities of our modular MEMS-Electronic-Photonic Heterogeneous Integration platform, combining III-V based MEMS tunable VCSELs with silicon photonic components and high performance CMOS integrated electronics. Such a compact on-chip FMCW LADAR source has broad military and civilian applications, including e.g. mobile 3D imaging, autonomous vehicles, 3D cartography or gesture based computing.

Keywords: Frequency Modulated Continuous Wave (FMCW); Laser Detection and Ranging (LADAR); Light Detection and Ranging (LIDAR); Micro-Electro-Mechanical System (MEMS); III-V semiconductor; tunable Vertical Cavity Surface Emitting Laser (VCSEL); Optoelectronic Phase Locked Loop (OPLL); CMOS; Silicon Photonics; 3D Integration; 3D Imaging; Short Wavelength Infrared (SWIR).

Introduction

3D imaging systems have become increasingly popular, among others in small form factor 3D scanners for 3D printing or as sensors in autonomous cars, such as the google self-driving car. Various technologies are employed in such systems. Indoor applications, such as the successful Microsoft Kinect, are commonly based on analysis of the projection of a specific spatial pattern [1] or on triangulation [2]. Most LIDAR systems used in autonomous cars are based on Time of Flight (TOF) range measurement [3]. Today’s systems are typically several cm\textsuperscript{3} in size and offer 10s of cm ranging resolutions at an object distance of 10m [4]. For better ranging resolutions, high speed detectors and electronics are required. An alternative approach consists in FMCW LADAR. Bench top systems have recently been demonstrated using MEMS tunable lasers [5]. This approach allows for better range resolution at smaller distances, without the need of high speed electronics. 31 µm range resolution at 1.5m has recently been reported [6].

FMCW LADAR

One possible approach for a FMCW LADAR system employs a linearly frequency swept laser source (Figure 1). The frequency of the reflected light from the target is compared to the laser frequency (local oscillator), and the frequency difference $f_{\text{beat}}$ encodes the target range

$$R = \frac{c f_{\text{beat}}}{2\gamma}$$

with $c$ the speed of light, and $\gamma = df / dt$ the frequency shift per unit time of the tunable laser source (frequency ramp rate). A central part of the imaging system is thus the generation of a linearly frequency swept source. In the LADAR system being developed, the frequency ramp is generated using an optoelectronic feedback loop, with a tunable MEMS VCSEL center wavelength of 1.55μm. In this short wavelength infrared (SWIR) range, high powers can be used for increased ranging distances and signal quality, while being eye safe, and imaging through humidity saturated environments such as clouds and fogs are possible.
**LADAR Chip Integration Strategy**

The chip scale LADAR source combines three distinct technologies into a single chip: III-V based MEMS tunable VCSELs [7], passive components and photodiodes in Silicon Photonics, and CMOS electronics (Figure 2). This approach allows maximum flexibility in assembly and optimization of the individual components. The process details are presented in the fabrication outline section below.

**Figure 2.** Schematic representation of the modular integration strategy, combining active III-V Devices, Silicon Photonics and CMOS Electronics.

The 3D integration allows a very compact form factor of the linearly swept frequency source. Figure 3 shows a 3D representation to scale (for reference: the through silicon via (TSV) are 200um in length). The total volume of the source is about 2mm³. Such a small form factor can enable completely new applications e.g. in mobile 3D imaging systems.

**Figure 3.** 3D model of the integrated chip scale LADAR source, including CMOS, silicon photonics and tunable MEMS VCSEL. The model is to scale; the thickness of the silicon photonics wafer is 200um.

**Linear Frequency Sweep Generation**

The FMCW LADAR source signal consists in a linear frequency sweep of a tunable VCSEL. The linear frequency sweep is generated using an optoelectronic feedback circuit, described by Satyan et al. [8]. The schematic circuit diagram of this optoelectronic feedback circuit is shown in Figure 4. The upper part of the figure also shows the detector part required for range measurements; this paper however, focuses on the FMCW LADAR source part. The color codes correspond to the three technologies employed for the specific functions: The active III-V tunable VCSEL (red) generates a frequency swept signal, which is fed into a Silicon Photonics Mach-Zehnder-Interferometer (MZI) (blue). The linearly swept signal produces a sinusoidal output at the detector, which is beaten with a reference oscillator to produce a dc signal. In the CMOS circuit (black), the dc part is integrated to form a linear ramp, which is then squared (‘predistortion circuit’), in order to account for the nonlinear tuning characteristics of the electrostatically tuned MEMS VCSEL.

![Figure 4. Circuit diagram representing the Optoelectronic Phase Locked Loop (OPLL) generating a broadband frequency chirp. The integration of the three different component system is represented in red (III-V), blue (Silicon Photonics) and black (CMOS electronics).](image)

A linear ramp is thus a self-consistent solution to this optoelectronic feedback circuit as described by Satyan et al. [8]. The loop integrator can be reset at the desired repetition frequency of the frequency chirp to produce a saw-tooth shaped output form, or using adequate signal processing, a triangular output waveform can be obtained. The range measurement in this closed loop operation simplifies to

\[
R = \frac{l_{ref}}{f_{ref}} \frac{f_{target}}{f_{ref}}
\]

**LADAR Source Chip Fabrication Outline**

Fabrication of the LADAR source chip consists of development of the MEMS tunable VCSEL [7], the silicon photonics circuits, and the CMOS drive circuit. The
individual components are designed and optimized individually. Figure 5 shows detail SEM recordings of a) the silicon photonics MZI (low loss waveguides and directional couplers) and b) the MEMS tunable VCSEL, both developed and fabricated at UC Berkeley; the CMOS circuit is custom designed and fabricated using commercial MPW runs.

![Figure 5. SEM images of a) silicon photonics MZI with low loss waveguides and directional couplers and b) MEMS tunable VCSEL.](image)

The three components are then assembled in two subsequent flip-chip bonding process steps. Figure 6 shows a schematic cross section view of the assembled chip scale LADAR source.

![Figure 6. Cross section of the complete LADAR source assembly.](image)

Integration of the VCSEL to the Silicon Photonics circuit is achieved using a AuSn eutectic bonding process step, ensuring electrical, mechanical and thermal interconnect. Figure 7 shows a 500 x 500 μm² VCSEL die placed with μm-accuracy flip-chip technology on a Silicon Photonics passives chip. Grating couplers on the Silicon Photonics chip are used for vertical I/O into 500 nm-wide single-mode TM waveguides.

The VCSEL to Silicon Photonics integration approach yielded successful lasing and coupling into the silicon photonics circuit, as confirmed by infrared imaging of the output ports of the integrated chip (Figure 8).

![Figure 7. Confocal microscope image of VCSEL die integrated on Silicon Photonics chip. Inset: emission view of stand-alone VCSEL (facing downwards for integrated chip). Output couplers are on left- and right-most regions.](image)

The integrated VCSEL current threshold was measured to be as small as 1.8 mA, with a continuous wave operation output power of 330 μW, maintaining fundamental transverse-mode operation across a wide range of biasing currents with a compact spot size (~ 5 μm).

![Figure 8. Profile of light collected at output couplers after traveling through 500 nm-wide single-mode TM Si waveguides. The inset shows the 2D intensity profile and the profile location (white dashed line).](image)

**Benchtop Demonstrator Ranging Results**

In order to demonstrate ranging using a frequency swept tunable VCSEL, we have previously presented a benchtop LADAR system using off the shelf components [10, 11]. The benchtop LADAR system allows testing of the individual components and the overall performance of the system. Figure 9 shows the typical response recorded at the photodiodes of the target beat signal and the MZI reference...
beat signals respectively. The distance measurement is retrieved from the ratio between the two beat signals weighted by $L_{\text{ref}}$, as depicted in Figure 10. The error bars designate one standard deviation over a full ramp sweep, which amounts to a ranging error of less than 0.5mm.

Figure 9. Typical recordings of the MZI reference and the target beat signals for a given linearly swept laser input.

Figure 10. Ranging measurements of a calibrated measurement. Standard deviation over one ramp sweep is less than 0.5mm.

Conclusions

We present advances in the development of a chip scale integrated FMCW LADAR source, combining MEMS tunable VCSELs, silicon photonics and CMOS electronics, generating a broadband linear frequency sweep. Such a linearly swept frequency source can be used for accurate ranging, as we demonstrate with sub-mm resolution ranging using a bench top model FMCW LADAR source. We propose a wafer level integration strategy of the optoelectronic feedback circuit for a chip-scale FMCW LADAR source chip. Such a chip scale LADAR source is expected to enable completely new applications, such as 3D-imaging in mobile applications and for autonomous vehicles, 3D cartography or gesture based computing.

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References