Frequency-modulated Continuous-wave LIDAR Module in Silicon Photonics

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Abstract: Frequency-modulated continuous-wave LIDAR is demonstrated with a silicon photonic device consisting of transmitting and receiving waveguides and photodetectors. A 20 mm resolution and 2 m range is shown. Simultaneous distance and velocity measurements are achieved.

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1. Introduction

Light detection and ranging (LIDAR) is a useful technology with applications such as autonomous vehicles [1], aerial mapping [2] and robotics [3] because of its high range and resolution. However, many current LIDAR systems are bulky and expensive which limits their use in applications where form factor and cost must be minimized. Integrated photonics provides a potential path for chip-scale LIDAR systems. Silicon photonics in particular offers a low chip cost technology that can be integrated with CMOS electronics [4, 5] and lasers [6, 7]. In an integrated setting, frequency-modulated continuous-wave (FMCW) LIDAR [8] offers an advantage over time-of-flight (TOF) detection techniques because avalanche photodiodes (APD) and high-speed electronics are not required. This allows for a simpler and more cost effective implementation.

In this paper, we demonstrate a silicon photonic FMCW LIDAR transmitter and receiver module. Two waveguide edge couplers are used as a transmitter and receiver and an adiabatic coupler is used to beat the received signal with a local oscillator that is measured with on-chip balanced photodetectors. A 20 mm resolution and 2 m range is demonstrated and simultaneous distance and velocity measurements are taken. This work demonstrates a chip-based device to perform ranging and velocity measurements and shows a combined transmitting and receiving LIDAR module in silicon photonics technology for the first time. Furthermore, the device was fabricated in a state-of-the-art CMOS foundry on a 300 mm wafer and can be mass-produced at a low chip cost.

2. Device Principles

The effective device is illustrated in Fig. 1(a). The full device was originally designed for heterodyne interferometry and is described in [9]. LIDAR measurements can be taken by only measuring the measurement arm. It was fabricated using 193 nm immersion lithography on a 220 nm thick silicon-on-insulator (SOI) wafer with 2 µm buried oxide

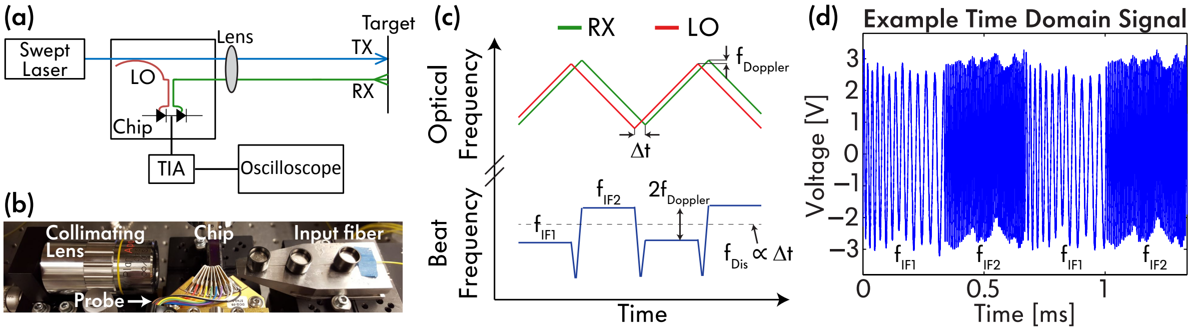

Fig. 1. (a) Illustration of effective device consisting of silicon photonics chip with collimating lens. Full device in [9]. (b) Image of optical setup showing input fiber, collimating lens, electrical probe and chip. (c) Concept of frequency-modulated continuous-wave LIDAR with triangular modulation. (d) Example time domain signal from the balanced photodetectors after a TIA for a moving target.

(BOX). A laser diode is coupled to the chip with an edge coupler. On chip, the optical power is split using an adiabatic coupler to act as a local oscillator (LO) and transmitted signal (TX). The TX signal is coupled off-chip with an edge coupler and then is collimated with a lens and incident to a target. Light reflected off of the target (RX) is received through another edge coupler and is beaten against the LO and input to on-chip balanced Ge photodetectors. The photodetectors are similar to those in [4]. An external transimpedance amplifier (TIA) is used to convert the photocurrent to a voltage which is analyzed by an oscilloscope. A photo of the setup is shown in Fig. 1(b).

The concept of frequency-modulated continuous-wave (FMCW) LIDAR with triangular modulation is illustrated in Fig. 1(c). For a stationary target, a single beat frequency occurs and is proportional to the distance to the target. For a moving target, two distinct beat frequencies occur in different time regions. The difference of these two frequencies is the Doppler shift that occurs when the transmitted light hits the moving target. The average of the two frequencies is proportional to the time-of-flight distance to the target. Fig. 1(d) shows an example time domain measurement of a moving target.

3. Homodyne Doppler Measurements

In order to test the receiving capabilities of the device and the electronics, homodyne Doppler measurements were taken. The concept of this measurement is shown in Fig. 2(a). A single pure CW laser is used for the TX and LO signals. The TX signal undergoes a Doppler shift when hitting a moving target, and when the RX is beaten against the LO, the Doppler beat frequency is produced. A 40 mW JDSU laser diode at 1543 nm was used as the laser source. The target was a cube reflector placed on a 1.5 m long Aerotech motorized stage with speed control up to 300 mm/s. The speed of the target was varied and the beat frequency was measured when the target was 1 m away from the device [Fig. 2(b)]. The beat frequency matched the theoretical Doppler shift for each speed. The speed error for each measurement is shown in Fig. 2(c). The maximum absolute error was 2 mm/s. The average and maximum relative error were 0.7% and 2.2% respectively, thus showing the accuracy of the receiving module of the device.

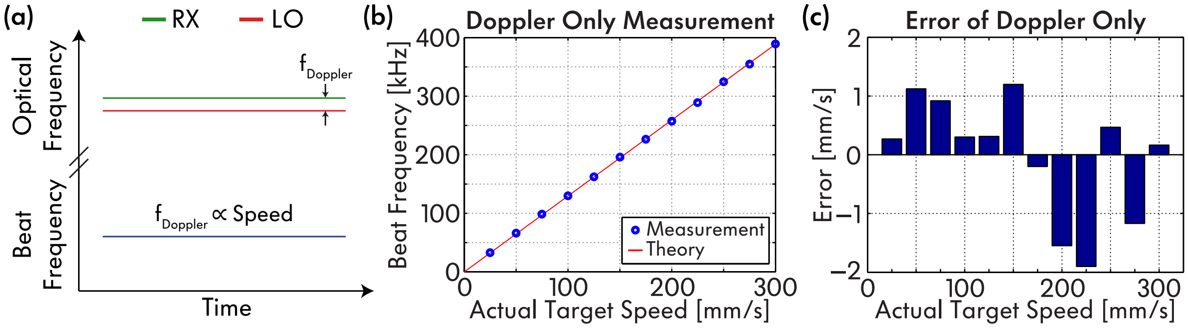

Fig. 2. (a) Concept of homodyne Doppler measurements. (b) Experimental results of the homodyne Doppler measurements with a theoretical line of the speed dependent Doppler shift. (c) Speed error of the data set in (b).

4. Frequency-modulated Continuous-wave LIDAR Measurements

FMCW measurements were taken by modulating the injection current of the laser diode. The injection current was modulated with an arbitrary function generator and the driving function was designed for a linear optical frequency sweep in a triangular fashion. Fig. 3(a) shows the measured beat frequency for a stationary target at varying known distances at 10 mm intervals. For this experiment, the laser injection current triangular frequency was 100 Hz and the resulting optical frequency sweep rate was 6.4 THz/s. A histogram of the error in the distance measurements is shown in Fig. 3(b). Absolute errors were less than 10 mm for distances up to 2 m, showing a noise-limited resolution of 20 mm. The maximum relative error was 0.75%. Measurements taken on separate days were seen to have similar error figures. FMCW measurements were then taken on a moving target at various speeds and distances. The laser current triangular frequency was increased to 5 kHz in order to increase the laser sweep rate to 190 THz/s. This was to ensure that the Doppler shift frequency would be less than the beat frequency seen for a stationary target. The two measured beat frequencies in the different time domain regions are shown in Fig. 3(c) along with the average beat frequency. A histogram of the distance error of these measurements is shown in Fig. 3(d), with a maximum absolute error of 20 mm and a maximum relative error of 3.2%. The calculated velocity of the target for each measurement is shown in Fig. 3(e) and a histogram of the error of velocity is shown in Fig. 3(f). The average relative error of the velocity measurement

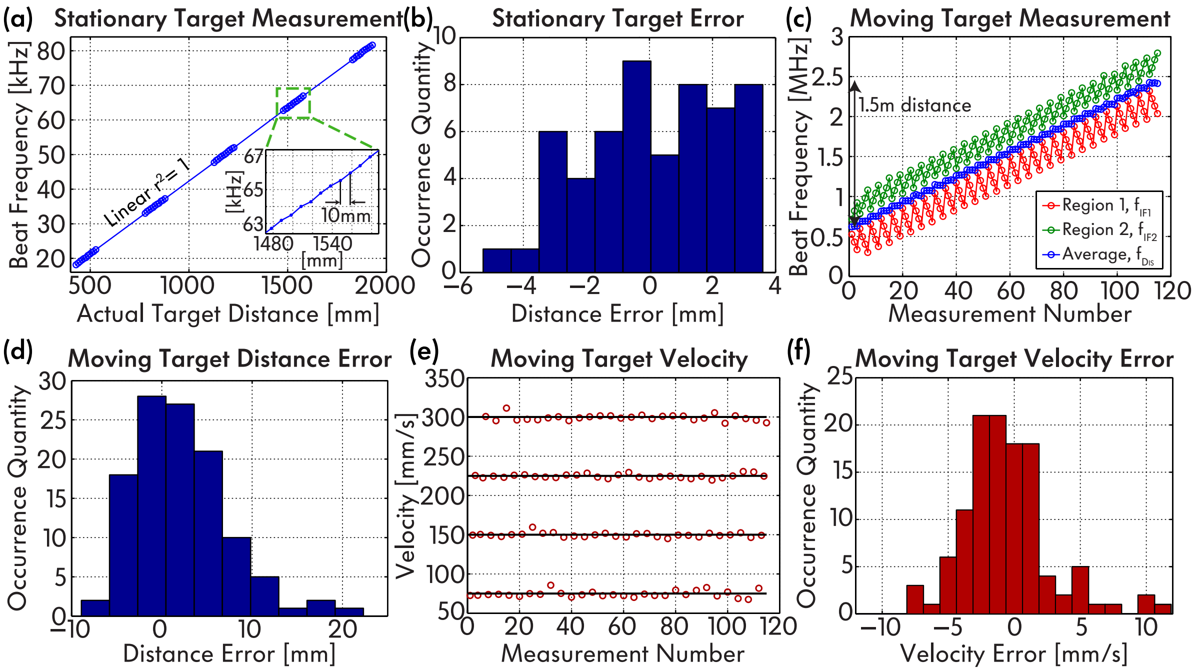

Fig. 3. (a) Measured beat frequency at various stationary target distances at 10 mm intervals. (b) Distance error of the measurements shown in (a). (c) Measured beat frequencies for a moving target while sweeping velocity and distance. (d) Error of calculated target distance of the data set in (c). (e) Calculated velocity of the data set in (c), black lines show actual velocity. (f) Error of calculated target velocity of the data set in (c).

was 1.9%. The overall increase of error in this experiment is caused by the faster laser sweep being slightly non-linear. Further optimizations on the linearity of the sweep could be performed using optoelectronic feedback [10].

5. Conclusions

Frequency-modulated continuous-wave LIDAR has been demonstrated with a silicon photonic device consisting of transmitting and receiving waveguides and photodetectors. Homodyne Doppler measurements and LIDAR with simultaneous distance and velocity measurements have been performed with respectable range, resolution and error figures. By integrating this device with a laser in a single package, a compact and mass-producible LIDAR system could be realized.

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