Compact QCL-based coherent LiDAR in the mid-infrared

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Frequency-modulated continuous-wave light detection and ranging (FMCW LiDAR) is a technique for fast and precise measurements of distances and speeds of hard and diffuse targets [1]. Moreover, the effects of feedback reinjection on the laser parameters, such as the optical power, wavelength or voltage can be utilized for numerous sensing applications [2]. We show the first experimental demonstration of a FMCW LiDAR in the mid-infrared, based on a novel self-mixing interferometry technique and compare it with a conventional mid-infrared FMCW system. Thanks to an injection current predistortion technique, high-speed and precise linear optical frequency modulation (LFM) up to 8 GHz in 1µs with less than 1% error to linearity is achieved, allowing a greater FMCW signal-to-noise ratio.

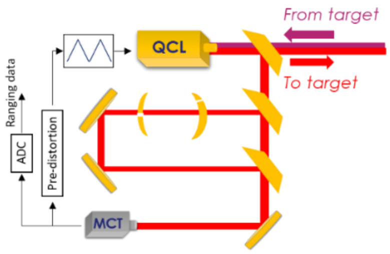

Figure 1 – Experimental setup of the Self-mixing interferometry LiDAR

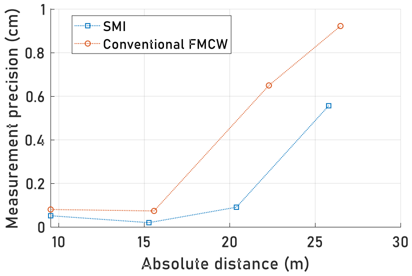

Figure 2 – Absolute distance measurements precision results

One part of the beam (> 90%) is sent to a target in order to perform distance & speed measurement. In the absence of optical isolation, a part of the reflected light will come back inside the laser cavity, interfering with the intracavity field. The changes induced simultaneously on the optical power and frequency are monitored on a photodiode at the output of the interferometer. More specifically, the measurement of the periodic perturbation on the LFM allows for speed and distance measurement, without adding any new components to the LFM system. Taking advantages of intrinsic high-speed dynamics of mid-infrared unipolar sources and detectors, we achieved kHz-rate sub-cm precision measurement of low-reflective targets at distances up to 25 m. Such results pave the way to systems more robust against meteorological perturbations and with an improved discreetness. Moreover, the overall compactness and robustness of the optical setup constitute a leap toward the development of mid-infrared quantum optoelectronic devices and their integration into components.

[1] Feneyrou, P., et al. "Frequency-modulated multifunction lidar for anemometry, range finding, and velocimetry–1. Theory and signal processing." Applied optics 56.35 (2017): 9663-9675 [2] P. R. Wallace, Phys. Rev. **71**, 622(1947).

[2] Rakić, A. D., et al. "Sensing and imaging using laser feedback interferometry with quantum cascade lasers." Applied Physics Reviews 6.2 (2019): 021320

Method

Measurement of absolute distance by swept-frequency self-mixing interferometry has been previously demonstrated with quantum cascade lasers in the THz and short-infrared ranges [3]. The method usually consist in sweeping the frequency of the laser by modulating the injection current with a triangle-shaped waveform, and measuring the changes in the QCL voltage. However, the intrinsic inertia of the thermal effects behind the optical frequency modulation induce a non-linear optical frequency waveform, reducing the signal-to-noise ratio (SNR) or giving rise to intricate compensation algorithms. Furthermore, the measurement technique is only sensitive to the laser diode voltage variations. In this paper, we use a predistortion algorithm to linearly sweep the frequency of the laser, enhancing the FMCW SNR [1]. Moreover, we sense the speed and distance of the target by directly measuring the periodic perturbations induced simultaneously on the optical power and frequency by means of an intensity measurement at the output of an interferometer. Therefore, one single signal is used both to monitor/correct the optical frequency chirps and to measure the effect of the feedback from the target on the laser. This way, we benefit from the stability and high signal-to-noise ratio of the coherent interferometric measurement without adding any complexity to the setup. The technique is illustrated in Fig. 3 & 4, where the blue signal correspond to the voltage on the photodiode at the output of the interferometer when no light is reinjected. In this case, the linear frequency chirps are monitored and adequately corrected. The orange curves correspond to the signal when light reflected from the target is reinjected into the laser. The frequencies of the perturbations on the optical frequency chirps, highlighted in Fig. 4, can be directly utilized to measure the speed and distance of the target.

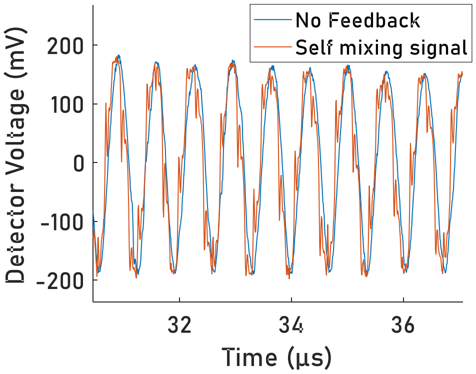

Figure 3 – Time signal of the interference fringes at the output of the interferometer

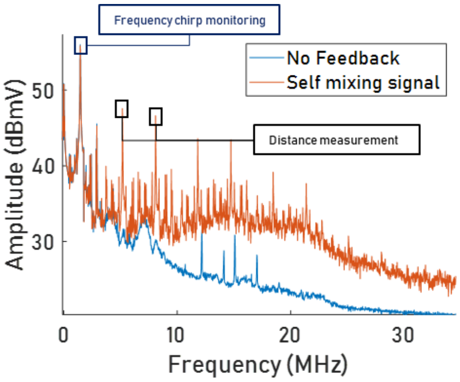

Figure 4 – Spectrum of the interferometer output

Finally, this technique rely on the physical self-mixing model both for high and low feedback ratio. In this way, the system is relevant for distance and speed measurement of low reflective and long distance targets, as shown within the experimental demonstration developed in the next section.

[3] J. Keeley., et al, "Three-dimensional terahertz imaging using swept-frequency feedback interferometry with a quantum cascade laser," Opt. Lett. 40, 994-997 (2015)

Experimental demonstration & detailed results

The experimental setup described in the first section is shown below. The output of a 9-µm QCL is sent to a compact Mach-Zehnder interferometer composed of a Herriott cell, allowing long optical path difference, here 6 m, in a small volume. The detection of the interferometer output is made with a MCT detector, as presented in the ‘Self mixing interferometry LiDAR’ part of Fig. 5. The other part of the beam is sent toward the target to be measured. Moreover, the results are compared with a commercial red telemeter and a conventional FMCW coherent detection, as presented in the ‘Conventional FMCW detection’ of Fig. 5. In order to illustrate the long-distance ranging capabilities of the method, the distance of a corner-cube reflector (CCR) has been measured in an outdoor experiment up to 25 m, as illustrated in Fig 6.

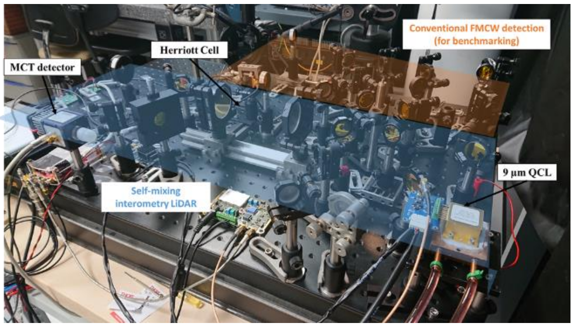

Figure 5 – Detailed photograph of the experimental setup.

Figure 6 – Realization of outdoor distance measurement

The total integration time is 1 ms, allowing for kHz-rate distance measurement. As shown in Fig. 7, the distances are measured with a sub-cm precision to a distance up to 25 m. Higher distances shall be demonstrated. The measurement are compared with a commercial red telemeter, and the accuracy of the mid-infrared LiDAR is below ~5 cm. It appears from the precision and accuracy measurement that the performance of the setup compares with conventional, but more cumbersome, FMCW LiDAR technique.

Thus, these results substantiate the possibilities of mid-infrared LiDAR systems with very low size, weight and power constraints. Finally, it is important to highlight the possibility to sense not only the distance, but also the reflectivity of the target through self-mixing techniques, opening the path to a wide scope of applications such as spectroscopy or coherent communications.

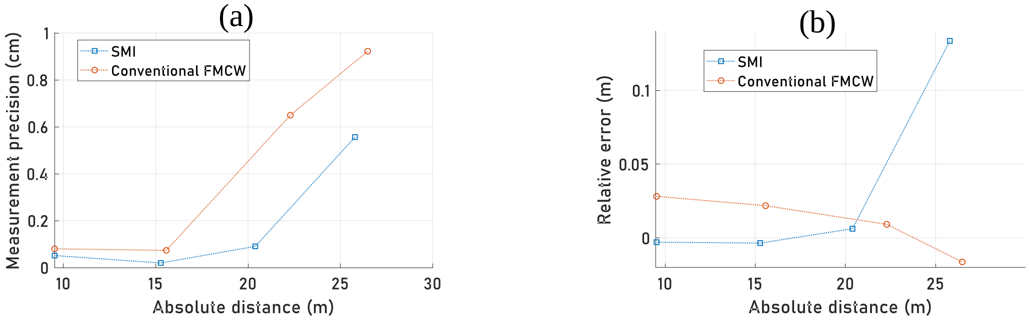

Figure 7 – Results of the distance measurement. (a) - Relative Error to the commercial red telemeter (b) - Measurements precision