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Long-wave infrared FMCW ranging systems based on external coherent detection and self-mixing interferometry

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Abstract: Long-wave infrared (LWIR) wavelengths are expected to provide a better robustness against meteorological perturbations as well as an increased covertness for hard target FMCW LiDAR. However, the implementation and modulation of LWIR sources and detectors constitutes an important challenge. With a custom quantum cascade detector, we demonstrate for the first time a QCL-based FMCW ranging system up to 50 m on an outdoor static target, with a < 2 % relative precision. It relies on the linear optical frequency modulation of the QCL, up to 8.4 GHz in 65 µs with 0.03 % of nonlinearities. Furthermore, through a novel method of self-mixing interferometry, we exploit the laser perturbations caused by optical feedback to perform FMCW ranging with fewer components. Similar results are obtained with both architectures, opening the way to low-complexity LWIR FMCW systems, where the low maturity of optical isolators and components makes it a critical asset.

1. Introduction

Frequency-modulated continuous-wave light detection and ranging (FMCW LiDAR) allows for fast and precise measurements of distances and speeds of hard and diffuse targets [1]. Moreover, recent interest in the study of mid-wave (3-5 µm) and long-wave (8-12 µm) infrared wavelengths underline potential advantages in advert meteorological conditions [2], as well as an improved covertness.

Thanks to the implementation of state-of-the-art unipolar optoelectronic components, we demonstrate and compare kHz-rate mid-infrared outdoor distance measurement up to 54 m with two frequency-modulated ranging techniques.

The first technique, called external coherent detection (ECD), relies on a conventional FMCW architecture based on the coherent detection of the received signal on a quantum cascade detector (QCD) designed and fabricated by the LPENS. The second technique, called self-mixing, utilizes the perturbations of the laser properties caused by the reinjection of the received light in the laser cavity to retrieve the ranging information.

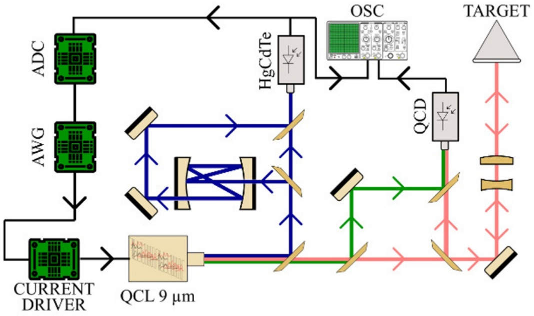

Figure 1 - Optical architecture of the LWIR FMCW LiDAR.

2. Experimental setup

The experimental setup is presented in Figure 1. The light from a 9 µm QCL is modulated in frequency through a current modulation and split in two. One part of the beam (in blue in Fig. 1) is sent to a Mach-Zehnder calibration interferometer. It acts as a frequency discriminator to convert optical frequency modulations into intensity fluctuations, measurable with a commercial HgCdTe quadratic detector. From the measurement of the frequency modulation and thanks to an iterative predistortion algorithm [3], the waveform of the laser current modulation is optimized to obtain a linear frequency modulation. The obtained results are plotted in Fig. 2. The span of the frequency modulation reaches 8.42 GHz in 65 µs, and the nonlinearities account for 0.03 % of the modulation span over the center of the slope (90 %), used as the range of interest.

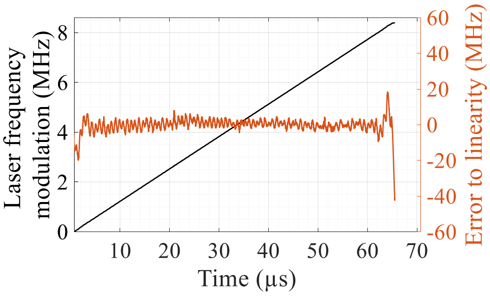

Figure 2 – Linear frequency modulation results

The rest of the optical power is split in two. One part is used as a local oscillator (in green in Fig. 1) and sent directly toward the quantum cascade detector. The other half (in pink in Fig. 1) is sent into free space toward the target to be measured. The light reflected by the target is collected and sent to the QCD. There, a beatnote at a frequency f_{FMCW} rises from the difference in frequency between the received light and the local oscillator. It is linked to the distance of the target by:

$$f_{FMCW} = \frac{-2\beta d}{c} \tag{1}$$

Where β is the frequency modulation rate in Hz/s, d the distance of the target in m and c the speed of light in m/s.

3. Self-mixing interferometry

The second method studied in this work relies on so-called self-mixing effects. There, the light reflected by the target is reinjected inside of the laser cavity. The reinjected light interferes with the intra-cavity field, leading to fluctuations of the laser properties (optical power, frequency and diode voltage). These perturbations contain, as already reported in previous works, the information on the target distance [4], [5].

We propose a method to retrieve the distance information from the perturbations of the frequency modulation. These perturbations are measured at the output of the calibration interferometer, and the external QCD is not required anymore.

This method is based on the measurement of the optical phase perturbations, more affected by self-mixing effects than intensity perturbations in DFB QCL. This last point is attributed to the very high-frequency of the relaxation oscillations in QCL [6].

At the output of the interferometer, the perturbation of the frequency modulation rising from the self-mixing effect creates additional oscillations at frequencies

$$f_{SMI} = \frac{-2\beta d}{c} \pm \beta\tau_{MZ} \tag{2}$$

Where τ_{MZ} is the time delay of the Mach-Zehnder interferometer in s.

To illustrate the signal of interest obtained in the two methods, an example of the measurement spectra obtained with both techniques is illustrated in Fig. 3. The two measurements are made with a target at a distance of ~ 15 m. A slight difference in the absolute distance of the target between the two measurements explains why the ECD peak is not exactly centered between the two SMI peaks.

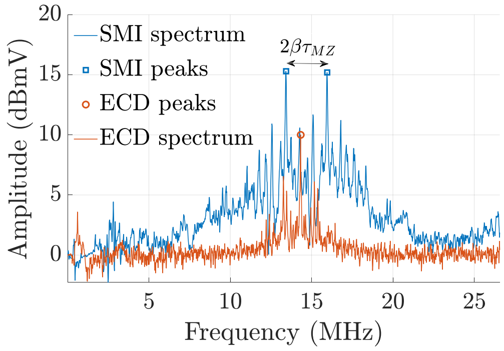

Figure 3 – Measurement spectra of the ECD and SMI technique for a target at 15 m

4. Ranging results

Both FMCW ranging techniques (external coherent detection and self-mixing) are demonstrated through the ranging of a remote corner-cube retroreflector at up to 53 m. The measured distance is compared with a reference measurement made with a red rangefinder.

The results obtained with a 1 ms integration time are plotted in Figure 4. The standard deviation over 100 measurements (Fig. 4-(a)), accounting for the precision of the measurement, is centimetric up to 25 m for both techniques and stays below 2 % of the absolute distance up to 50 m. These fast and precise measurements are achieved thanks to the high-speed, linear and wideband frequency modulation presented previously.

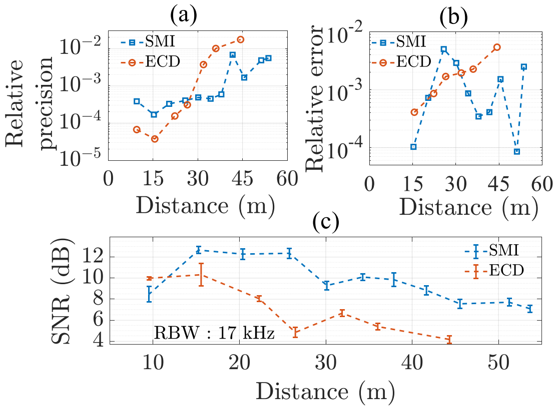

Figure 4 – Results of the FMCW distance measurement with ECD and SMI techniques. (a) – Relative standard deviation (b) – Relative error (c) – Signal-to-noise ratios

The accuracy is quantified by the difference between the measured distance and the reference measurement in Fig. 4-(b). Interestingly, the self-mixing technique exhibits better overall performances than the conventional ECD technique. It is illustrated by the better signal-to-noise ratio (SNR) obtained with the SMI technique in Fig. 4-(c). The higher SNR is attributed to the fact that the SMI technique is self-aligned; the target's normal reflection is intrinsically aligned with the laser cavity, facilitating the experimental implementation. This advantage is of critical importance in LWIR optical systems where alignment constraints are significant.

A major limitation of both techniques lies in the frequency noise of the laser. Uncontrolled optical phase fluctuations decrease the temporal coherence between the local oscillator (alternatively the intra-cavity field) and the received signal. The resulting noise on the frequency of the signal of interest decreases the overall signal-to-noise ratio and hinders the distance measurement. A practical tool to estimate at which distance these effects significantly undermine the coherent ranging is the coherence length. It is assessed experimentally by a measurement of the frequency noise through the delay-line method.

We estimate the coherence length of the system to be around 20 m. Although not an intrinsic limitation, it underlines the need to stabilize the laser frequency for the measurement of longer distances.

5. Conclusion

This contribution exhibits an experimental demonstration of FMCW mid-range distance measurement in the long-wave infrared, based on unipolar components. The overall results demonstrate high-speed and precise ranging obtained thanks to a linear, fast and wideband optical frequency modulation. To adapt to the strong alignment constraints of free-space long-infrared systems, we focused on a second FMCW technique based on self-mixing effects. With both techniques, the obtained precision stays below 2 % of the absolute distance up to 53 m for a 1 ms integration time. Interestingly, the self-mixing technique performs better than the one based on an external coherent detection. This observation paves the way to short-distance high-speed and precise mid-infrared ranging while strongly reducing the complexity of the system, a critical asset considering the low maturity of components in this wavelength range. An increase in the maximum achievable distance is expected from a reduction of the laser linewidth.

Overall, these demonstrations contribute to better understand the expected performances and limitations brought by state-of-the-art quantum cascade components in FMCW ranging systems. The expected increase of the performances and maturity of these components in the coming years opens the path for efficient long-wave infrared ranging systems and to other applications as spectroscopy based on optical frequency modulation.

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