Coherent interferometric dual frequency laser radar for precise range/Doppler measurement

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Abstract—A novel coherent interferometric dual frequency laser radar that merges the concept of laser and radio detection and ranging (ladar and radar respectively), for both range and velocity measurement, is presented and experimentally demonstrated. The innovative architecture combines the broadband tunability of dual-wavelength optical sources, enabling a dynamic trade-off between precision and robustness in Doppler estimation, with the high stability of low frequency RF sources for the interferometric measure of the target range with extreme accuracy. The possibility to easily reconfigure the employed frequencies, allows to change the Doppler resolution, as well as the range ambiguity and precision, to dynamically adapt the system to reliably operate in different environments. Moreover, the coherent detection allows to enhance the signal to noise ratio reaching excellent performances also with low level of received power. The laboratory characterization provides an estimation of the system performances, in terms of resolution and sensitivity, as well as the indoor demonstration with targets of opportunity proves the effectiveness of the proposed architecture to operate in real scenarios.

Index Terms—laser radar, coherent detection, range and Doppler measurements.

I. INTRODUCTION

OVER recent years, thanks to the innovation in optical and electro-optical components, light (or laser) detection and ranging (LIDAR or LADAR) systems are having great success, proving themselves as a considerable alternative to passive radiometers or microwave sensors [1]. LADAR sensor emits energy in the optical frequency range (many order of magnitude greater than radars) retrieving information about the target of interest by collecting the backscattered light. Although the principle of operation is the same of radar systems, there are many differences between light and microwave sensing. For example, radars are widely used in all day/weather conditions being robust to atmospheric turbulences, also demonstrating penetration capabilities. Nevertheless they have poor cross range resolution, lack in velocity estimation of slow targets, and are vulnerable to radio interference sources also demonstrating high probability of

intercept [2]. Besides, LADAR systems allow higher directionality thanks to the very narrow beam divergence capable to solve small targets, and are a limited source of interferences with low probability of intercept. Nevertheless they present high sensibility to the atmospheric condition, and a limited range because of particle absorption [3]. LADAR applications include target detection and ranging, gas and particle size [4] detection and recognition (via differential absorption and scattering), vibrometry [5], imaging [6], synthetic aperture imaging [7] and more over. Depending on the application, LADARs can exploit incoherent or coherent detection. Optically incoherent schemes, which resort to intensity modulation and direct detection (IMDD), are only used for range extraction, while optically coherent architectures are used to obtain both range and Doppler measurements, exploiting the phase information of the optical wave. [8]. Moreover, IMDD systems that resort to amplification stages at the receiver are limited by the amplified spontaneous emission (ASE) noise, thus one of the main advantages of optically coherent detection can be identified in an amplification gain which allows to increase the signal to noise ratio (SNR) and the sensitivity of the system.

Three different incoherent techniques are often used to extract range information of the targets: pulses time of flight distance measurement, phase shift range finder and phase/frequency modulated pulses [9]. The first one is based on short pulse emission and the relative measurement of the round trip time between transmission and echo reception. Range resolution and ambiguity directly depend on pulse width and repetition interval while precision also depends on receiver noise contributions. The phase shifts technique is based on optical power modulation via a constant radio frequency tone at the transmitter side, and phase detection at the receiver. The selection of the radio frequency carrier determines the maximum range ambiguity of the system, while signal to noise ratio (SNR) influences the phase estimation and consequently the range precision. Going forward, in phase/frequency modulation laser radar system, the basic principle of pulse compression technique is exploited to increase the range resolution. For example linear or non-linear frequency modulated optical carriers are used to determine target range through a beat frequency estimation between a reference and the backscattered optical signals. The time bandwidth product of the employed waveform guarantees good range resolution performances. Other examples of different modulation techniques, such as stepped frequency pulses, complementary

Manuscript received on January 15, 2016.

This work has been carried on within EU projects RAPIDO, ROAM, PETRA, and FiWin5G.

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code generation, and sparse frequency chirp are detailed in [10],[11],[12].

On the other hand, a direct measurement of the velocity can be reached by using coherent LADAR systems, which measure the Doppler shift experienced by the optical beam. They are widely used for atmospheric sensing [13], wake vortex risk mitigation [14],[15] aerosol, clouds, gases tracking [16], and more besides. Basically, in a coherent laser radar architecture, the back reflected light from a target is compared with a nominal reference wavelength, thus determining the occurred Doppler shift [17][18]. Nevertheless the speckle noise, induced by target's roughness and atmospheric turbulence [19], causes spectral broadening of the Doppler shifted line, thus limiting the spectral resolution of the sensing system [20]. In order to reach high robustness against the speckle noise, coherent dual-frequency lidar (DFL) architectures are exploited [21]. In these systems, the measurement of the Doppler shift is obtained as a difference among the Doppler shift of two locked continuous waves. In all the coherent techniques, the maximum observable range is relative to the coherence length of the employed laser source, thus ultra stable optical sources, e.g. mode-locked lasers (MLL) [22], are used to extend the monitored range. The authors in [23] investigated an architecture in which different couples of modes from a MLL are used to emulate different microwave frequencies for Doppler detection. Nevertheless, such implementation is not able to provide information about the target's distance.

In this paper we propose and implement, for the first time to our knowledge, a coherent interferometric dual frequency laser radar (IDFL) for simultaneous velocity and range measurements. The architecture resort to the principle of the DFLs to perform Doppler processing and to the principle of differential interferometric phase estimation for the extraction of the range information. The details of the principle of operation are described in section II. The laser radar demonstrator has been tested with cooperative targets and the obtained results, for both range and speed measurements, are presented and discussed (section III), demonstrating the effectiveness of the proposed approach.

II. PRINCIPLE OF OPERATION

The proposed architecture exploits two phase locked optical carriers, modulated by a low frequency RF tone, to gather information about both distance and speed of the illuminated target. The scheme of the operation principle is depicted in Fig.1. The two optical carriers are generated by a tunable dual frequency laser source (T-DFL), which could be implemented resorting, e.g., to a coherent frequency comb [24], a MLL [23], or directly to a dual frequency laser [25]. The two modes present electrical fields $E_1(t)$ and $E_2(t)$ centered at the optical frequencies ν_1 and ν_2 , respectively, separated by Δf (Fig.1-A). The resulting electrical field $E(t)$ can be expressed as:

$$E(t) = E_1(t) + E_2(t) = A_1 \exp(i \cdot 2\pi \nu_1 t) + A_2 \exp(i \cdot 2\pi \nu_2 t) + c.c. \quad (1)$$

where A_1 and A_2 are the amplitudes of the two carriers. For simplicity their phases are supposed equal and null. This optical signal is then split and sent to the transmission and

reference path respectively. The reference replica is frequency shifted by f_{IF} , as represented in Fig.1-B, in order to be able of evaluating the sign of the target velocity, and can be written as

$$E_{REF}(t) = \frac{A_1}{\sqrt{2}} \exp[i \cdot 2\pi(\nu_1 + f_{IF})t] + \frac{A_2}{\sqrt{2}} \exp[i \cdot 2\pi(\nu_2 + f_{IF})t] + c.c. \quad (2)$$

The other replica is modulated in a Mach-Zehnder modulator (MZM), biased in carrier suppression mode, by a RF tone with frequency f_M and, for simplicity of notation, phase $\phi_M=0$. Four optical tones are thus created as depicted in Fig.2-C, so that their electrical field can be represented as:

$$E_M(t) = B_1 \exp[i \cdot 2\pi(\nu_1 - f_M)t] + B_1 \exp[i \cdot 2\pi(\nu_1 + f_M)t] + B_2 \exp[i \cdot 2\pi(\nu_2 - f_M)t] + B_2 \exp[i \cdot 2\pi(\nu_2 + f_M)t] + c.c. \quad (3)$$

Fig. 1. Top: scheme of principle of the proposed architecture-DFL tunable dual frequency laser, MZM Mach Zehnder modulator, DSP digital signal processing. Bottom: Optical and electrical spectra at different points of the scheme of principle.

with B_1 and B_2 amplitude terms. These two couples of modes, separated by a frequency $2f_M$, will be exploited for the interferometric estimation of the target range. Furthermore, since their central frequencies ν_1 and ν_2 are in turn separated by Δf , the experienced differential Doppler can also be estimated [23]. This signal is transmitted through a telescope to the target which reflects it back. The backscattered signal, after experiencing a time delay and a Doppler shift (Fig.2-D), can be written as:

$$E_{BS}(t) = C_1 \exp[i \cdot 2\pi(\nu_1 - f_M + \delta_{1A})t - i \cdot 2\pi(\nu_1 - f_M)\tau] + C_1 \exp[i \cdot 2\pi(\nu_1 + f_M + \delta_{1B})t - i \cdot 2\pi(\nu_1 + f_M)\tau] + C_2 \exp[i \cdot 2\pi(\nu_2 - f_M + \delta_{2A})t - i \cdot 2\pi(\nu_2 - f_M)\tau] + C_2 \exp[i \cdot 2\pi(\nu_2 + f_M + \delta_{2B})t - i \cdot 2\pi(\nu_2 + f_M)\tau] + c.c. \quad (4)$$

where τ is the relative delay induced by the target position, C_1 and C_2 represent the fields amplitudes, and δ_{1A} , δ_{1B} , δ_{2A} , and δ_{2B}

represent the Doppler shifts, functions of the target velocity as well as the modes frequencies. In detail

$$\begin{aligned}\delta_{1A} &= 2\varepsilon(v_1 - f_M)/c \\ \delta_{1B} &= 2\varepsilon(v_1 + f_M)/c \\ \delta_{2A} &= 2\varepsilon(v_2 - f_M)/c \\ \delta_{2B} &= 2\varepsilon(v_2 + f_M)/c\end{aligned}\quad (5)$$

where ε represents the target speed and c is the speed of light. Since $f_M \ll \Delta f$ we can consider $\delta_{1A} \approx \delta_{1B} = \delta_1$ and $\delta_{2A} \approx \delta_{2B} = \delta_2$. An optical coupler combines echo signal $E_{BS}(t)$ together with the reference beam $E_{REF}(t)$, as shown in Fig.2-E. The re-coupled signal is sent to a photodiode (PD) where the tones are heterodyned together. Among all the generated terms, only five tones fold down to the analog to digital converter (ADC) bandwidth (Fig.1-F), and can be digitized. Four of these tones are generated by the coherent beating of $E_{BS}(t)$ with $E_{REF}(t)$ and their amplitudes are proportional to the amplitude of $E_{REF}(t)$, thus performing a coherent amplification of the backscattered signal. The fifth term instead is the direct detection of the modes separated by $2f_M$, which is very weak with respect to the coherent ones and can be neglected or filtered out. The output signal of the photodiode $I_{PD}(t)$ can be written as

$$\begin{aligned}I_{PD}(t) &= D_1 \exp[i \cdot 2\pi(f_{IF} + f_M - \delta_1)t - i \cdot 2\pi(v_1 - f_M)\tau] + \\ &+ D_1 \exp[i \cdot 2\pi(f_{IF} - f_M - \delta_1)t - i \cdot 2\pi(v_1 + f_M)\tau] + \\ &+ D_2 \exp[i \cdot 2\pi(f_{IF} + f_M - \delta_2)t - i \cdot 2\pi(v_2 - f_M)\tau] + \\ &+ D_2 \exp[i \cdot 2\pi(f_{IF} - f_M - \delta_2)t - i \cdot 2\pi(v_2 + f_M)\tau] + c.c.\end{aligned}\quad (6)$$

with D_1 and D_2 amplitude terms. These four terms suffer the previously mentioned spectral broadening due to speckle and ambient noise, and their frequencies can not directly provide a precise measure of the velocity of the target. Moreover to prevent aliasing and overlapping of the different frequency components, the condition $(f_{IF} + f_M) > \delta_{MAX}$ has to be satisfied, where δ_{MAX} is the maximum expected Doppler shift.

A square law operation on the electrical signal $I_{PD}(t)$ allows us to obtain the desired information of the target range and speed. Among all the generated terms, only the ones at lower frequencies are of interest, as depicted in Fig.1-G. In particular the term

$$P_r(t) = (D_1^2 + D_2^2) \cdot \exp[i \cdot 2\pi(2f_M)t - i \cdot 2\pi(2f_M)\tau] \quad (7)$$

contains the time delay information from which the target range can be extracted, and the term

$$P_v(t) = 2(D_1 \cdot D_2) \cdot \exp[i \cdot 2\pi|\delta_2 - \delta_1|t + i \cdot 2\pi(v_2 - v_1)\tau] \quad (8)$$

contains the information related to the differential Doppler $|\delta_2 - \delta_1|$ used for the measurement of the target velocity, while the phase term is ignored.

Assuming $|\delta_2 - \delta_1| < f_M$, the terms $P_r(t)$ and $P_v(t)$ can be extracted by means of a narrow digital band pass filter centered at $2f_M$, and a low pass filter spanning from DC to f_M , respectively, as shown in Fig.2-G.

The range processing resorts to the phase term of (7) induced by the delay τ , given by

$$\varphi_r = 2\pi(2f_M)\tau \quad (9)$$

The phase difference $\Delta\varphi = \varphi_r - \varphi_M$ provides the information about the target range R , and since the phase φ_M of the RF tone has been set equal to zero the target distance is:

$$R = \frac{c}{2} \cdot \tau = \frac{c}{2} \cdot \left[\frac{\varphi_r}{4\pi \cdot f_M} \right] \quad (10)$$

with an unambiguous range R_{NA} function of f_M , expressed as

$$R_{NA} = \frac{c}{2(2f_M)} \quad (11)$$

Concerning the target velocity measure, referring to (8), the estimation of the frequency $|\delta_2 - \delta_1|$ of the signal $P_v(t)$ provides information about the target speed ε without additional noise induced by target roughness and atmospheric turbulence [21]. Nevertheless the square law operation does not preserve the information of the movement direction (the sign of $(\delta_2 - \delta_1)$), thus the resulting velocity information is

$$|\varepsilon| = \frac{|\delta_2 - \delta_1|c}{2\Delta f} \quad (12)$$

The sign of the velocity vector ε can be recovered from (6) evaluating the direction of the frequency shifts experienced by the four tones due to the Doppler effect (see Fig.1-F).

III. EXPERIMENTAL SETUP AND RESULTS

To validate the concepts detailed in the previous section, the proposed laser radar has been implemented. The developed experimental setup is sketched in Fig.2. For simplicity, as dual frequency laser source a continuous wave (CW) laser modulated in carrier suppression is employed. It is driven by a 20 GHz oscillator, and a programmable clock divider provides the tunability of the modes' spacing.

On the reference path the frequency shift is obtained by means of an acousto-optic modulator (AOM) driven by a 40MHz RF source. On the other path the two laser modes are modulated with an RF synthesizer via a MZM biased in carrier suppression. The resulting optical signal is boosted up to 30dBm with an erbium doped fiber amplifier (EDFA), and it is sent to the target with a 3mm-aperture collimator. To avoid backreflections that could interfere with the phase estimation of the modulation tone, we avoid the circulator and collect the echo by another collimator with an aperture of 7mm, thus resorting to a bistatic implementation. The echo is coupled with the frequency shifted reference signal and then detected and amplified by an avalanche photodiode (APD) and its transimpedance amplifier (TIA). Finally a 100Msp/s 14-bit ADC digitized the photodiode's signal, as well as the modulation signal that will be used to determine the propagation phase delay.

Fig. 2. Experimental setup. CW: Continuous Wave Laser, AOM: acousto optic modulator, MZM: Mach Zehnder modulator, ADC: analog to digital converter, CKD: Clock Divider.

The laser radar has been first tested targeting a static target at different positions to extract the range information and the relative precision of the measure. An example of the FFT spectrum of the acquired signal is depicted in Fig.3, employing 40GHz detuned modes (i.e. avoiding the clock divider) and a modulation frequency $f_M=3\text{MHz}$. With respect to Fig.1-F, only two tones at 37MHz and 43MHz are present since the target is not moving, i.e. $\delta_1=\delta_2=0$. The FFT in Fig.3 presents spurious tones due to the non ideality of the exploited test set up. In detail, a strong peak at 40MHz is caused by the non ideal carrier suppression of the MZM and the residual unshifted signal of the AOM. Moreover a weak tone at 6MHz, generated by the direct detection of echo signal not amplified by the coherent detection, is also visible.

Fig. 3. FFT spectrum of the signal in the static target case, employing $\Delta f=40\text{GHz}$ and $f_M=3\text{MHz}$.

Since these non idealities are known, they can be easily digitally erased before the squaring operation. In fact the range measurements confirm the effectiveness of the scheme. Fig.4 reports the measured ranges of the target with respect to its real positions, for different values of the modulation frequency. The coherent integration time was set to 500ms. As can be seen, the range precision increases with the modulation frequency. In fact, the range error ζ depends both on the signal to noise ratio (SNR) of the digitized signal as well as on f_M [26]:

$$\zeta \cong \frac{\lambda/2}{10^{\left(\frac{\text{SNR}}{20}\right)}} = \frac{c}{2 \cdot 10^{\left(\frac{\text{SNR}}{20}\right)} \cdot f_M} \quad (13)$$

Nevertheless even with $f_M=500\text{kHz}$, that gives an unambiguous range of 150m, the maximum occurred error is no greater than 1.4cm, while, with a modulation frequency of 6MHz (12.5m of unambiguous range), this error is drastically reduced to 4mm. These results was obtained with a measured received power of about -60dBm.

Fig. 4. Measured distances of the target with respect to its real positions, for different modulation frequencies.

The system has thus been tested varying the received power via a variable optical attenuator. The results are reported in Fig.5, that shows the standard deviation of 50 10ms-long measures with a modulation frequency of 3MHz, keeping the target stationary at about 1m from the telescopes. A collected power of -45dBm gives a standard deviation of only 350μm. Reducing the power, the precision remains below 5cm (0.2% of the unambiguous range) down to -70dBm, and could be still acceptable even at -90dBm. In fact, below this value the standard deviation rises up to about 70cm, i.e. 2.5% of the considered range.

Fig. 5. Standard deviation of the measured range vs the optical power collected by the receiver telescope.

Beside the static characterization, the developed laser radar system has been tested in the detection of moving targets. To this extent, Fig.6-A reports the acquired spectrum in the case of a target under uniform rectilinear motion. As can be seen, with respect to Fig.3 $\delta_1 \neq \delta_2 \neq 0$ and the four tones detailed in (6) appear as two broadened spectral lines centered at $f_{IF}+f_M+(\delta_2+\delta_1)/2$ and $f_{IF}-f_M+(\delta_2+\delta_1)/2$ respectively. The inset in Fig.6-A shows these broadened spectral components. According to (5), since $\delta_2 < \delta_1 < 0$, i.e. negative Doppler shift,

the target is moving away with respect to the laser radar sensor. In fact, after squaring equation (6) the sign of the Doppler shift is lost, and it needs to be evaluated here. To obtain a precise estimation of the velocity, a 100ms portion of the temporal trace of the ADC output signal is squared, and the tone at $|\delta_2 - \delta_1|$ is highlighted with a frequency resolution of 10Hz, as shown in Fig.6-B, so that its peak at 260Hz can be appreciated. Since the employed emulated microwave frequency is 40GHz, the measured Doppler shift corresponds to a velocity of 0.975m/s. The position and velocity of the target over 1s, as measured by the developed system, are depicted in Fig.6-C. The range linearly increases according with the negative Doppler shift, and since in 1s it covers about 1m, a speed of 1m/s can be estimated. Considering the discrete 10Hz resolution, i.e. an uncertainty of 0.0375m/s according to equation (12), this perfectly matches the measured Doppler.

Fig. 6. A) FFT of the signal acquired by the ADC in the case of a moving target; B) FFT of the squared signal; C) Range and velocity as measured by the laser radar system.

Since the developed system has been demonstrated and characterized both with static and uniformly moving targets, to better prove its effectiveness further trials with randomly moving targets have been carried on. In these tests, reported in Fig.7, the integration time was reduced to 20ms to avoid spreading in the Doppler spectrum, as well as in the range determination. This resulted in a reduced frequency resolution down to 50Hz, thus increasing the uncertainty of the measured velocity. Moreover to highlight the flexibility of the proposed architecture different parameters have been employed. For the measure in Fig.7-A the generated modes present a detuning of 20GHz (i.e. the RF oscillator is divided by a factor of 2), and a modulation frequency $f_M=3\text{MHz}$ has been used. The second measure, reported in Fig.7-B, employed a mode spacing of 40GHz and a modulation frequency of 6MHz. In both the experiments the target firstly moves away from the telescope, then comes back, and changes again its direction. The measured velocity always follows the range variations, in particular can be appreciated that whenever the direction of the motion changes, the velocity crosses the zero value. The

finite frequency resolution affect the velocity measurement as visible in the resolution steps. Since the test range is about 16m long and in the second measure the $f_M=6\text{MHz}$ unambiguous distance results 12.5m, a portion of the trace is aliased at lower distance. Nevertheless this does not influence the measure of the velocity, which doesn't present discontinuities.

The proposed architecture thus demonstrated its capability to precisely measure both the range and the velocity of an arbitrary target, even with different f_M or Δf configurations.

Fig. 7. A) Range and velocity measure of a randomly moving target, $\Delta f=20\text{GHz}$ and $f_M=3\text{MHz}$; B) Range and velocity measure of a randomly moving target, $\Delta f=40\text{GHz}$ and $f_M=6\text{MHz}$.

IV. DISCUSSION AND CONCLUSIONS

In this paper, a novel architecture for a coherent interferometric dual frequency laser radar has been proposed, theoretically analyzed, and experimentally demonstrated. The scheme exploits the broadband tunability of a dual-wavelength optical source to precisely estimate the target velocity via differential Doppler measure, and the high stability of a low frequency RF source for the interferometric measure of the target range with extreme accuracy. This way, both the data are extracted from a single measure.

In particular, the DFL technique provides velocity information immune to the speckle noise induced by target's roughness and atmospheric turbulence, which causes spectral broadening and limits the resolution of the sensing system. Moreover the possibility to adjust the frequency spacing of the employed laser modes permits to adapt the system's resolution

to the observed situation, e.g. reducing the emulated microwave frequency Δf for vibrating targets or increasing it to detect very slow drifts. The interferometric approach for the range measure instead guarantees an extreme accuracy despite the narrow bandwidth, thus allowing the use of low sample rate digital electronics. Moreover the frequency modulation signal can be easily tuned, thus adapting the system range resolution and ambiguity to the scenario. In details, lower frequencies can be employed to roughly determine the target distance, and a higher frequency, with a reduced unambiguous range, can provide a precise measure.

Furthermore, the coherent detection avoids the noisy EDFA at the receiver stage, and increase the sensitivity with low optical echoes, allowing a size reduction of the focusing optics, thus reducing their weight and cost, and a lower transmitted power, thus increasing the safety and reducing the power consumption.

All these peculiarities has been experimentally validated, characterizing the system in different conditions. The spatial resolution reached millimeters accuracy and hundred meters unambiguous range. The velocity estimation matched the range variation with the only limit of the discrete FFT spectral resolution, providing a 10Hz precision. Moreover the sensitivity measure demonstrated an error <1% even with a collected received power of -90dBm.

Therefore, the validation of the proposed architecture demonstrates its suitability in applications where harsh environment requires high level of reconfigurability between precision and robustness.

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