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SOFTWARE DEFINED COHERENT LIDAR (SD-CL) ARCHITECTURE

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I. INTRODUCTION

In recent years, thanks to the innovation in optical and electro-optical components, space based light detection and ranging (Lidar) systems are having great success, as a considerable alternative to passive radiometers or microwave sensors [1]. One of the most important applications, for space based Lidars, is the measure of target's distance and its relative properties as e.g., topography, surface's roughness and reflectivity, gravity and mass, that provide useful information for surface mapping, as well as semi-autonomous landing functionalities on low-gravity bodies (moons and asteroids). These kind of systems are often called Lidar altimeters or laser rangefinders.

Up to now, Lidar sensors employed in already lunched or planned missions (Mercury Laser Altimeter – MLA [2], Advanced Topographic Laser Altimeter – ATLAS [3], BepiColombo Laser Altimeter – BELA [4], etc.) resort to a time of flight (ToF) configuration based on short pulse emission, with incoherent detection at the optical receiver. The main advantage of ToF technique lays in the capability to improve the range resolution and the ambiguity range just reducing the pulsewidth and increasing the pulse repetition time respectively, and in the use of a highly consolidated technology. On the other hands the main disadvantage of this technique is the need of high pulse energy to increase the Lidar sensitivity and consequently the maximum observable range, with consequent limited components lifetime [5].

In order to reach high distances with low peak power, preserving a high range resolution, a coherent approach can be introduced at the receiver side. It guarantees a coherence gain at hardware level due to the presence of a high power local oscillator at the photodetector, increasing the system sensitivity. A typical radar compression method, instead of the ToF technique can be exploited, where a amplitude/phase/frequency modulation is applied to a CW or a pulsed signal in order to increase the bandwidth and consequently the range resolution, without reducing the pulsewidth that results in a peak power growth [6]. The employment of amplitude/phase/frequency modulated CW waveforms instead of pulsed waveforms, further contributes to maintain a low transmitted peak power.

Moreover the same optical payload, equipped with a proper waveform, can be also employed for optical communications. In fact deep space optical communications are considered very attractive because of the higher bitrate that enhance the scientific return of the missions. Some examples of this optical systems on specific missions are the Lunar Laser Communication Demonstration on LADEE for NASA [7], and Optel-D on AIM for ESA [8]. Therefore, the possibility to share most of their communication hardware for sensing applications would be extremely attractive, reducing both the size, weight, and power consumption (SWaP) as well as the overall cost and complexity of the spacecraft.

In this paper, we propose and demonstrate an innovative software defined coherent Lidar (SD-CL) based on CW compression technique, that allows to perform long-range detection with high range resolution and reduced transmitted peak power. By sharing almost entirely its transmission subsystem, the proposed solution can be also integrated in modern spacecrafts that already employ photonics for space optical communications, thus minimizing the requested additional payload.

II. OPERATION PRINCIPLE

In the proposed architecture the system fires a CW carrying a pseudorandom bit sequence (PRBS), and resorts to the coherent detection to receive the echo. This way the unambiguous range is given by the duration of the bit sequence, while the range resolution depends only on the bitrate. Moreover, thanks to its optically coherent nature, the echo reception does not require ultra-sensible and delicate avalanche photodiodes (APD).

The scheme of principle of the proposed lidar is sketched in Fig.1. The signal to be transmitted is generated by a narrow linewidth DFB laser at 1550nm, whose output is splitted onto two different paths. On one path the CW feeds the coherent receiver, while on the other one it is ON/OFF modulated in a Mach-Zehnder modulator driven by a bit pattern generator (BPG) providing the PRBS. The resulting signal is finally boosted by an erbium doped fiber amplifier (EDFA) and transmitted to the target. It is worth noting that this part represents also a free space optical communications transmitter, in which the transmitted waveforms and data are completely software defined.

At the receiver side the echo is coupled with the previously spilled unmodulated signal, acting as local oscillator (LO), in a 90° hybrid optical coupler, whose outputs are detected by two balanced P-I-N photodiodes and finally digitized by two analog to digital converters (ADCs). Once in the digital domain, the signals from the ADCs are joined to produce a complex data (I + jQ) which is cross correlated with the transmitted bit sequence. The peak of the cross correlation gives the delay experienced by the echo, thus providing the information needed to calculate the target distance. Multiple detections can be coherently integrated to enhance the signal to noise ratio (SNR) and increase the sensitivity.

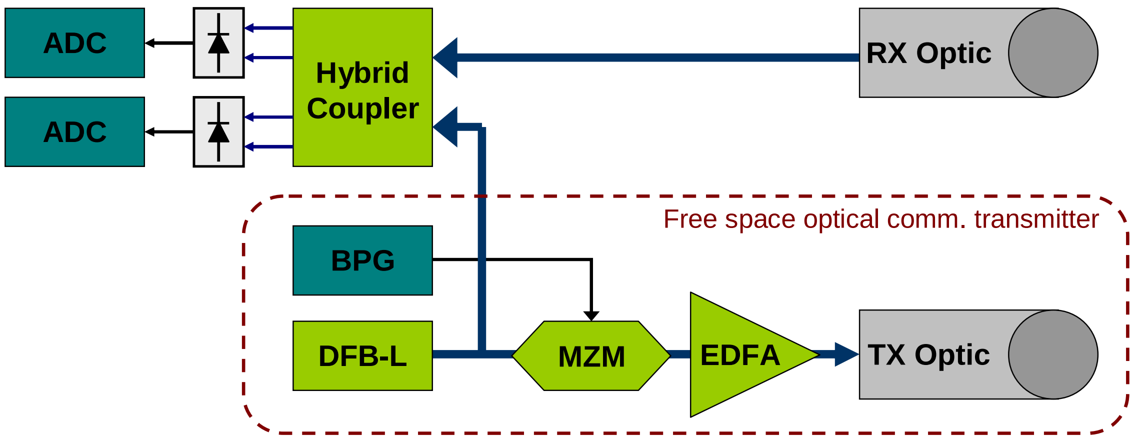

Fig. 1. Scheme of principle of the proposed LIDAR architecture. ADC: analog to digital converter; BPG: bit pattern generator; DFB-L: distributed feedback laser; MZM: Mach-Zehnder modulator; EDFA: erbium doped fiber amplifier.

III. EXPERIMENTAL SETUP AND RESULTS

The system has been experimentally implemented resorting to a 1Gsample/s BPG, thus obtaining a range resolution of 15cm, generating a 2^20-1 long PRBS which allows an unambiguous range of 150km. The DFB-L, driven at 250mA, provides 8dBm of optical power, and the LO power is 5dBm. Finally, the employed EDFA gives an output power of 20dBm. At the receiver side, the outputs of the photodiodes are amplified by two 20dB-gain low noise amplifiers (LNAs) with a bandwidth of 1GHz and a noise figure of 2.5dB, and are digitized by two channels of a 2.5Gsample/s 12bit real time oscilloscope. In order to emulate the observation of a distant target, the output signal is attenuated with a precise digital variable optical attenuator (VOA) and delayed with different spools of standard single mode fiber. Moreover, to take into account also the effects of a lambertian target, the signal is fired on a fixed paper target and the backscattered light is recoupled into the optical fiber, by means of a couple of collimators, as reported in Fig.2.

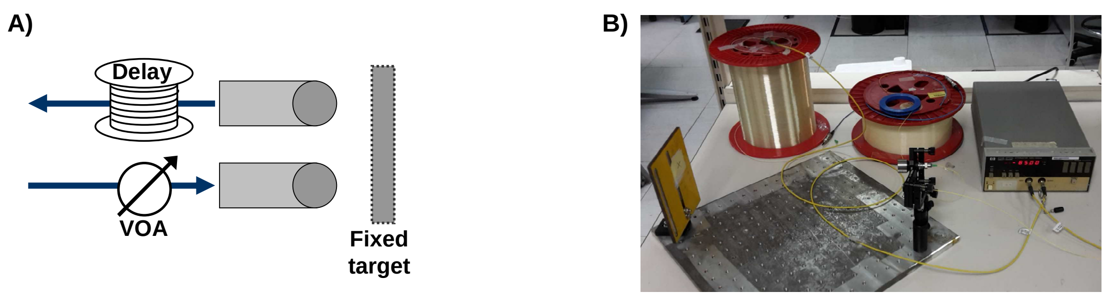

Fig. 2. A) Scheme of the setup employed to emulate different targets. VOA: variable optical attenuator. B) Picture of the setup.

The proposed architecture has been first characterized in terms of sensitivity. Fig.3 shows the obtained detection SNR, varying the received power and the integration time. The delay is constant and given by a fiber spool about 20km long. As can be seen, the SNR linearly decreases while reducing the power, and presents a 3dB increase doubling the integration time. Moreover it can be observed that for high powers the system saturates, thus SNR is limited to about 25dB. Nevertheless with an integration time of 64ms, i.e. summing 64 1ms-long acquisitions, it is possible to precisely detect an echo as weak as -90dBm, and increasing the number of measures to 256 even a -95dBm signal can be observed. The insets report the crosscorrelation functions corresponding to different points of the chart, with the range axis scaled to take into account the refractive index of the fiber.

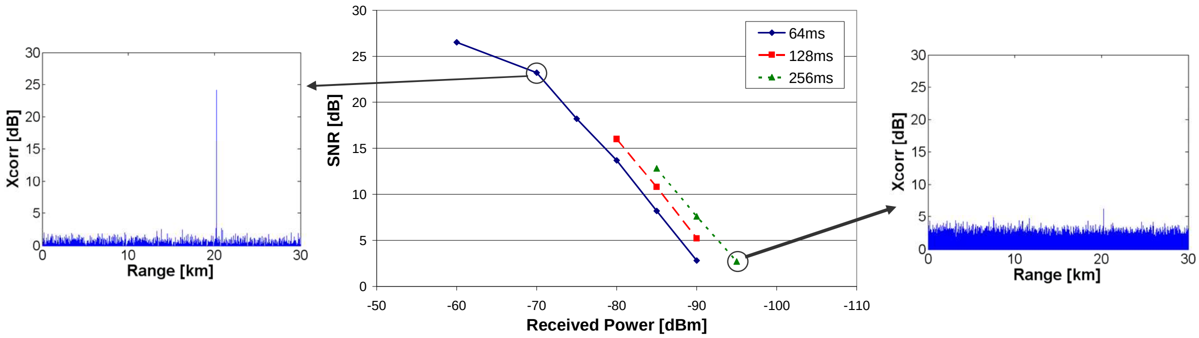

Fig. 3. Obtained SNR for different received powers and integration times. Insets: crosscorrelation functions of different points of the chart.

In order to demonstrate the range accuracy of the system, other measures have been carried out varying the fiber delay and keeping constant the integration time at 64ms and the received power to -80dBm. Fig.4-A reports the measured ranges employing different spools of fiber, with a length of about 1km, 11km, 12km, and 20km, respectively. As can be seen the systems presents almost equal performance, thus demonstrating the ability of detecting targets in a wide range of distances.

Since from such long ranges is not possible to appreciate the resolution of the system, additional measures resorted to the same 20km long fiber spool, while adding short patchcords. In details, Fig.4-B shows the range profiles employing just the spool (blue), and adding 22cm (red), 60cm (green), and 82cm (black). Given the 1.5 refractive index of the optical fiber the theoretical range resolution is 10cm, and in fact the four different peaks appear well separated and perfectly matching the length of the patchcords.

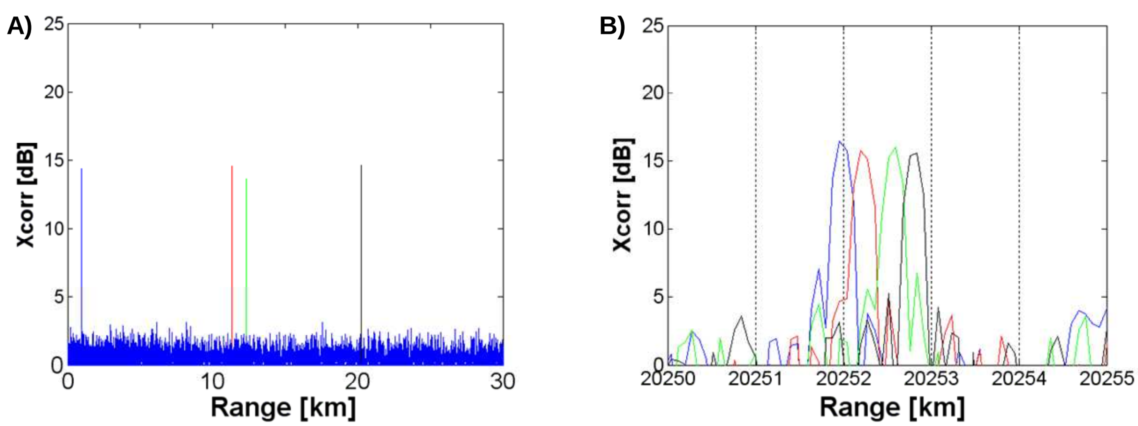

Fig. 4. A) Measured range profiles for different fiber spools. B) Range profiles adding short patchcords to the 20km fiber spool.

IV. CONCLUSIONS

We have proposed an innovative software defined coherent Lidar (SD-CL) architecture based on optically coherent detection. With this solution we have demonstrated the ability to perform long range detection resorting to the waveform compression on CW approach instead of classical ToF techniques. Moreover, since deep space optical communication payloads are going to be employed in many modern spacecrafts, the proposed solution allows the sharing of the hardware for both sensing and communication functionalities, thus minimizing the additional payload with a consequently reduction of mission cost.

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