Sequence-Coded Coherent Laser Range Finder

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Abstract: A range finder based on an extended sequence of coded pulses is demonstrated. Coherent detection is used to measure the range of weak point reflections, with average energy of only 0.15 photons per code symbol. © 2019 The Author(s)

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1. Introduction

Optical measurements of the distance to a target are used in many civilian and military applications. Laser range finders form the basis of light-radars (lidars), which are the sensors of choice in many autonomous vehicles [1]. Most range-finders rely on the transmission of short, intense and isolated laser pulses and time-of-flight measurements of reflected echoes. However, the transmission of high-peak-power pulses restricts the choice of available laser sources and may be intercepted by an adversary. Alternatively, distance can be measured by continuous transmission of modulated waveforms [2]. The entire energy of a carefully-designed, long sequence of pulses can be compressed into a short and intense "virtual pulse" by post-detection processing [2]. The instantaneous power of the transmitted waveform is orders of magnitude lower than those of single-pulse range finders. Therefore, sequence-coding can be realized using simple direct modulation of low-cost semiconductor laser diodes.

Effective protocols for the compression of incoherently-detected, unipolar sequences of pulses were proposed and demonstrated experimentally [3,4]. However, the sensitivity of simple direct detection is restricted by additive detector noise. Furthermore, incoherent detection is insensitive to phase information and limits the choice of sequences that may be used. In recent years, coherent detection has been widely adopted in optical communication, and coherent receivers have become increasingly available [5]. More than ever before, optical coherent detection can be leveraged towards additional applications such as precision reflectometry [6].

In this work, we report a proof-of-concept laser reflectometry experiment which combines pulse sequence compression and coherent detection of weak reflected echoes. Reflections from the far end of an optical fiber were used as point targets. The length of the fiber could be measured for very weak collected echoes, down to an average optical power of -85 dBm. Compared with our previous work using incoherent compression of the same pulse sequences, the receiver sensitivity is improved 20-fold and the acquisition duration is reduced by a factor of 400.

2. Experimental setup and results

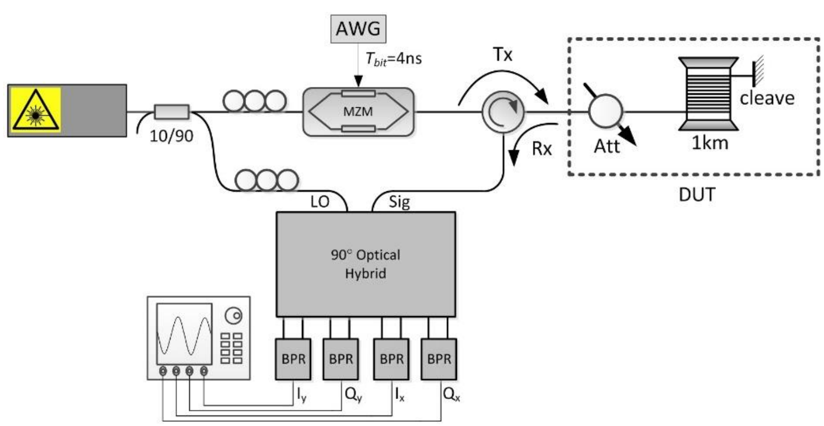

Figure 1. Schematic illustration of the experimental setup of a sequence-coded, coherent laser range-finder. AWG: arbitrary waveform generator; MZM: Mach-Zehnder electro-optic modulator; Att: variable optical attenuator; BPR; balanced photo-receiver; LO: local oscillator; Sig: range-finder signal path; DUT: device under test; Tx: transmission path; Rx: Receiving path.

An illustration of the experimental setup is shown in Fig. 1. Light from a laser diode at 1550 nm wavelength was split into two paths. Light in one branch was used as a local oscillator (LO) for coherent detection. Light in the other branch passed through an electro-optic amplitude modulator, which was driven by an arbitrary waveform generator. The instrument repeatedly generated a unipolar representation of a 4,003 bits-long Legendre binary sequence [4,7]. The modulation rate was 250 Mbit/s, corresponding to a ranging resolution of 60 cm in air (or 40 cm over fiber).

The coded signal was launched into a 1 km-long fiber under test through a circulator. Fresnel back-reflection from the remote end of the fiber propagated back through the circulator. A variable optical attenuator was used to control the average optical power P_{rec} of the collected back-reflection. The reflected echo interfered with the LO in a dual-polarization, 90˚ optical hybrid module (KyLia COH28). Four mixing replicas were detected by balanced photo-detectors, implementing both phase and polarization diversity. The four outputs were sampled by a digitizing oscilloscope at 2 Giga-samples per second for further offline processing. The detected waveform was digitally-filtered and compressed by cross-correlation with a carefully constructed reference sequence, following the protocol of [3,4,7]. Traces were acquired over several durations, corresponding to multiple periods of the modulation sequence.

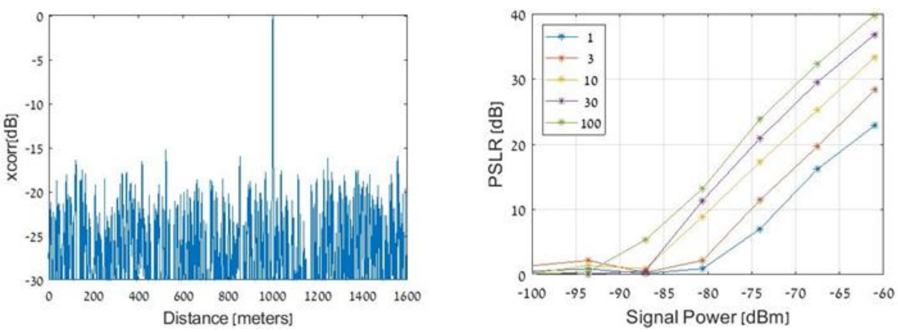

Figure 2. Left – Compressed form of a coded sequence, following reflection from the far end of a fiber under test. The average power of the collected echo was attenuated to -81 dBm. The collected waveform included 100 repetitions of the transmitted sequence, with overall acquisition duration of 1.6 ms. The point reflection is clearly identified above the background of noise-induced correlation sidelobes. Right – Power ratio between the main correlation peak due to the end-reflection and the strongest noise-induced sidelobe, as a function of the average power of the collected reflection. Several acquisition durations are presented, corresponding to different numbers of sequence repetitions (see legend).

Figure 2(left) shows an example of the compressed form of the coded sequence, following reflection from the far end of the fiber. The optical power P_{rec} of the reflected echo was attenuated to -81 dBm. The waveform consisted of 100 repetitions of the transmitted sequence, with an overall duration of 1.6 ms. The LO power was 16 mW. A peak corresponding to the point-reflection at the far end of the fiber is clearly observed. The full width at half maximum of the compressed peak is 35 cm, in agreement with expectations. The power ratio between that peak and the strongest noise-induced sidelobe (peak-to-sidelobe ratio, or PSLR) is 13 dB. Figure 2(right) shows the measured PSLR as a function of the average power of collected waveforms. Traces are shown for several acquisition durations, between 1 and 100 repetitions of P_{rec}. At the longest duration tested (1.6 ms), range could be measured for P_{rec} of -83 dBm. For comparison, our earlier experiments involving incoherent compression of the same sequence required 640 ms-long acquisition to properly process a trace with P_{rec} of -70 dBm. The average collected energy within each 4 ns-long code symbol in the current experiment was 2e-20 J, which equal 15% of the energy of a single photon. Such weak replicas of the transmitted sequence cannot be compressed using direct, incoherent detection.

The added value of coherent detection in improving the sensitivity of a sequence-coded laser range-finder has been demonstrated experimentally. The ranging resolution and sensitivity of the setup can be further improved beyond those of the current preliminary demonstration. Ongoing and future work looks to carry over the coherent compression of phase-coded sequences, which are widely employed in radars [2], towards optical reflectometry measurements, and to identify fundamental noise restrictions.

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