DTU Library

Coherent lidar modulated with frequency stepped pulse trains for unambiguous high duty cycle range and velocity sensing in the atmosphere

Lindelöw, Per Jonas Petter; Mohr, Johan Jacob

Link back to DTU Orbit

Coherent lidar modulated with frequency stepped pulse trains for unambiguous high duty cycle range and velocity sensing in the atmosphere

Petter Lindelöw and Johan Jacob Mohr

Ørsted•DTU, COM•DTU

Technical University of Denmark

Kongens Lyngby, Denmark

pli@oersted.dtu.dk

Abstract— **Range unambiguous high duty cycle coherent lidars can be constructed based on frequency stepped pulse train modulation, even continuously emitting systems could be envisioned. Such systems are suitable for velocity sensing of dispersed targets, like the atmosphere, at fast acquisition rates. The lightwave synthesized frequency sweeper is a suitable generator yielding fast pulse repetition rates and stable equidistant frequency steps. Theoretical range resolution profiles of modulated lidars are presented.**

Keywords: coherent lidar; frequency modulation; frequency step; frequency sweeper; LSFS; high PRF; range unambiguity

I. INTRODUCTION

Coherent lidar is a technology suited for remote wind velocity sensing [1]. Range resolved wind velocity is typically found from the Doppler shift and the time of flight of scatter generated by a coherent laser pulse reflecting off aerosols. The resulting range gated Doppler power spectra from typically thousands of pulses are accumulated to improve the accuracy since the received scatter from clear atmospheres are weak and speckled. The three dimensional wind velocity vector is constructed by probing in several directions. The pulse repetition frequency (PRF) is principally limited by range ambiguities. Focused cw systems and frequency modulation techniques have been used to increase duty cycles [2, 3]. However, focused systems are limited in range and rely on atmospheric homogeneity [4]. Saw tooth chirping is unsuitable for range resolved velocity sensing of the atmosphere since it introduces irresolvable range-Doppler ambiguities.

This paper proposes and describes a FM technique based on Frequency Stepped Pulse Trains (FSPT) suitable for high duty cycle range resolved coherent lidar sensing of primarily dispersed moving targets. FSPT modulation provides a unique range-cell to frequency-slot mapping, thus avoiding range and range-Doppler ambiguities. FSPT modulated continuously emitting lidars could potentially reach the resolution of low duty cycle systems based on short high peak power pulses.

Multi-frequency carrier wave systems based on range gating of pulses containing several frequencies simultaneously have previously been proposed [5]. The advantage being that the resulting spectra contained a comb of Doppler peaks related to the wind velocity. However, such solutions do not permit for a faster PRF without compromising the range ambiguity.

Recently several commercial initiatives, most notably Qinetiq's Zephir and Leosphere's Windcube, have been launched targeting the wind power industries need for remote wind velocity sensing in the first 200 m. Initial applications are site evaluation and power curve verification but also as a diagnostic tool. Future commercial applications might include airport wind surveillance and active wind turbine control. Existing cw lidar designs can be modified to use FSPT modulation with minimum changes to the transmitter side using a Lightwave Synthesized Frequency Sweeper (LSFS). Such systems will be insensitive to cloud induced range ambiguities and the range resolution at long distances will be improved. FSPT can also be employed to provide faster acquisition rates than in current low PRF systems.

II. METHOD

A single frequency coherent lidar emitting a frequency f_{trans} generates Doppler shifted scatter from a moving target with frequency $f_{rec} = f_{trans} + f_D$ where $f_D = 2v_{LOS}/\lambda$ and v_{LOS} is the target's line-of-sight velocity. The received backscatter beats with a reference local oscillator (LO) in a square law detector to form a heterodyne signal current. The LO has a frequency f_{LO}, possibly offset from the transmitted frequency by a known f_{offset}, i.e $f_{LO} = f_{trans} - f_{offset}$. The generated heterodyne signal will have an intermediate frequency $f_i = f_{rec} - f_{LO} = f_D + f_{offset}$, typically of some MHz, from which the Doppler shift can be deducted. When sensing a dispersed moving target, like the atmosphere, the heterodyne signal will contain a spectrum of frequencies, here referred to as a peak. The peak represents a speckle take of the wind distribution in the volume contributing with scatter during the sampling duration.

An FSPT modulated lidar emits a train of pulses. The carrier wave frequency is stepped between consecutive pulses by an equidistant step, Δf. The FSPT is further more described by the duration of fixed frequency, T_{pulse}, and the duration without emission, T_{inter}, according to Fig. 1.a. In a preferred embodiment the pulses are emitted without intervals, i.e. $T_{inter} = 0$ s. The train is thus emitting continuously and is only pulsed in the sense that the emitted frequency steps every T_{pulse}. An

FSPT modulated lidar will concurrently receive Doppler shifted and frequency stepped light scattered from several range sets of the atmosphere as illustrated in Fig. 1.b. Mixing this scatter with an LO and Fourier transforming the beat signal will give a heterodyne spectrum with a set of separate peaks each representing speckle takes of the wind velocities in the respective range set. If the frequency step is larger than the plausible variations in Doppler shift, the detected peaks will be uniquely allocated in a specific closed range of frequencies. Such frequency ranges will be referred to as frequency slots, shown in Fig. 1.c.
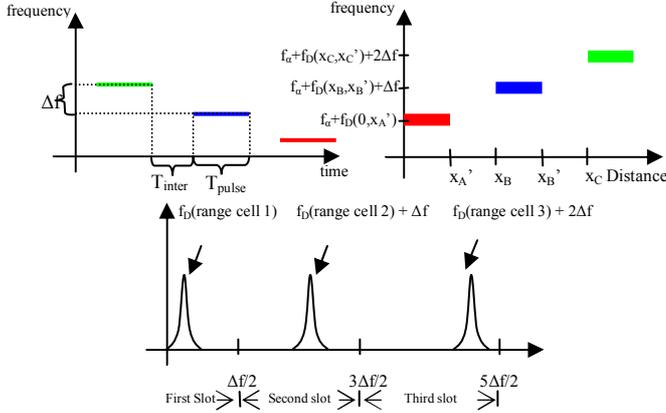

Figure 1 a) An FSPT with pulse duration, T_{pulse}, interpulse duration, T_{inter}, and pulse-to-pulse frequency step, Δf. b) Frequency as a function of scattered distance received by the lidar at time t_α when a full pulse has just been emitted. Note that the ranges contributing at t_α are $x_A' = (c/2)(T_{pulse})$, $x_B = (c/2)(T_{pulse} + T_{inter})$ and $x_B' = (c/2)(2T_{pulse} + T_{inter})$ etc. c) The scatter from the first three range cells mapped into their allocated frequency slots, $f_{offset} = 0$ MHz in this case.

The LO of an FSPT modulated lidar is a copy of the emitted train, possibly delayed with T_{delay}. Triggered sampling for one spectrum is done during a full LO pulse of duration T_{pulse}. The range set contributing to the peak in a specific frequency slot during a full sampling period will be referred to as a range cell. Each range-cell is continuously and uniquely mapped into its allocated frequency slot since the scattered frequency keeps its relation with the LO over consecutive pulses if the train parameters are effectively constant, as in Fig. 2.
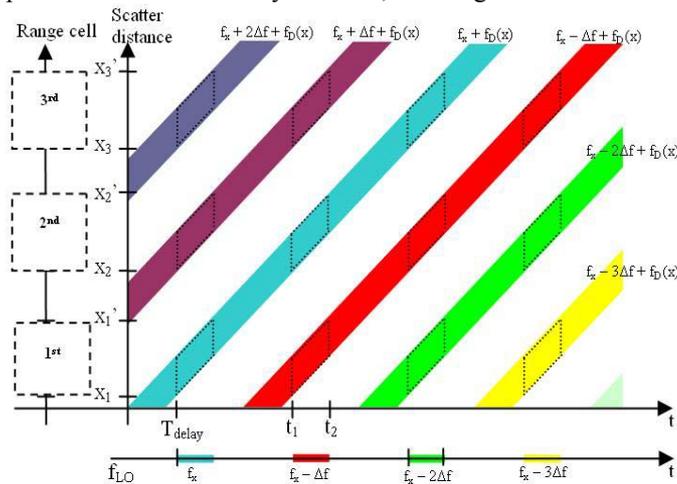

Figure 2: Time-space representation of scatter detected by an FSPT modulated lidar with a delayed LO and a considerable inter pulse duration for clarity.

E.g. The scatter received from the second range cell, x_2 to x_2', at time T_{delay} to $T_{delay} + T_{pulse}$, illustrated by the first purple parallelogram from the left, will generate a peak at $(f_x + \Delta f + f_D(x_2..x_2')) - f_x = \Delta f + f_D(x_2..x_2')$ when mixed with the LO pulse of frequency f_x. The scatter received from the same range cell at $t_1 = T_{delay} + T_{pulse} + T_{inter}$ to $t_2 = T_{delay} + 2T_{pulse} + T_{inter}$, the second light blue parallelogram from the left, mixed with the LO pulse of frequency $f_x - \Delta f$, will generate a second speckle take of the wind distribution in the second range cell, likewise allocated into the second frequency slot. Range cell i extends from x_i to x_i' described from

$$x_i = \left(T_{delay} + (i-2)T_{pulse} + (i-1)T_{inter}\right) \cdot \frac{c}{2} \qquad (1)$$

$$x_i' = \left(T_{delay} + i \cdot T_{pulse} + (i-1)T_{inter}\right) \cdot \frac{c}{2} \cdot \qquad (2)$$

Note that the first range cell will be cropped if $T_{delay} < T_{pulse}$ and that neighboring cells will overlap partly if $T_{pulse} > T_{inter}$.

Range cell i will generate a Doppler peak in frequency slot i extending from f_i to f_i' according to

$$f_i = f_{offset} + \left(i - \frac{3}{2}\right) \cdot \Delta f \qquad (3)$$

$$f_i' = f_{offset} + \left(i - \frac{1}{2}\right) \cdot \Delta f \cdot \qquad (4)$$

Note that the first frequency slot will include velocity ambiguities if $f_{offset} < \Delta f/2$, this ambiguity will reduce to an incapability to tell the sign of the wind velocity in the first range cell if $f_{offset} = 0$.

The line-of-sight wind distribution in range cell i is found from

$$v_{LOS} = \frac{\lambda}{2}\left(f_{peak} - (i-1)\Delta f\right) \cdot \qquad (5)$$

The train length will be limited in any embodiment. However, the FSPT can be restarted at the initial frequency if the train repetition frequency is low enough to ensure that the return from previously emitted trains can be disregarded. Note that during the first n LO pulses of a train only n+1–i returns will arrive from range cell i. Trains will typically contain more than hundred frequency stepped pulses in suitable embodiments. Inter-train ambiguities will therefore be unlikely and initial return losses will be insignificant.

III. RANGE RESOLUTION

All scatter distances within a range cell will not contribute with the same amount of energy to the allocated frequency slot. Aerosols in the beginning and the end of a range cell will contribute to the peak for a much shorter time than the aerosols in the middle of the range cell. The duration that aerosols at distance x backscatter a frequency allocated to frequency slot i, during the LO triggered sample duration T_{pulse}, is denoted $\tau_i(x)$ and given as

$$\tau_i(x) = T_{pulse}\left(1 - \left|\frac{x - c_i}{c_i}\right|\right) \cdot \frac{c}{2} \quad \text{for } x_i < x < x_i' \qquad (6)$$

where $c_i = (T_{delay}+(i-1)\cdot T_{pulse}+(i-1)\cdot T_{inter})\cdot c/2$ is the center of range cell i.

Note that aerosols at the edges of a range cell will contribute to two frequency slots for high duty cycle trains with partly overlapping neighboring range cells, i.e. $T_{pulse} > T_{inter}$.

The FWHM range resolution of collimated systems will be $cT_{pulse}/2$ in accordance with single frequency pulsed range gated systems. The discrete Fourier transform will spread the contribution of the energy contributed by aerosols at the edges over a wider bandwidth, since the contribution to frequency slot i from aerosols at the edges will have a shorter duration than those in the center of range cell i. The power in the discrete frequency bin corresponding to the wind velocity in the center of the range cell will thus be additionally significant and the effective range resolution improved.

FSPT can with advantage be used in monostatic focused systems. A focused system drastically improves the received optic power and can improve the range resolution without deteriorating the frequency resolution. The range resolution of range cell i can be calculated from the received energy profile $W_i(x) = \tau_i(x)\cdot W_{focus}(x)$ where $\tau_i(x)$ is the normalized weight function for rectangular pulses due to the varying contribution time and $W_{focus}(x)$ is the normalized weighting due to the focused telescope [6].

IV. FREQUENCY STEPPED PULSE TRAIN GENERATOR

A suitable embodiment of an FSPT generator for coherent lidars is the lightwave synthesized frequency sweeper [7] (LSFS) shown in Fig. 3. The loop is seeded with a pulse of duration T_{pulse} from an amplitude modulated coherent laser, e.g. using a Mach-Zehnder (MZ) modulator to generate a pulse from a highly coherent fiber laser with incorporated fiber grating. The seed pulse is amplified by an erbium doped fiber amplifier (EDFA). Most of the amplified light is coupled to the telescope while a fraction reenters the loop to be shifted in frequency by Δf in an acousto-optic modulator (AOM). This new input pulse becomes the base for the following frequency stepped pulse of duration T_{pulse}. A filter suppresses the build up of ASE noise and a fiber optic loop delay ensures the separation of consecutive pulses. The LSFS can be restarted in less than a microsecond by closing the AOM and letting the MZ generate a new seed pulse. The AOM gives a stable frequency step, the MZ can from practically rectangular pulses with good extinction ratio and the emission can be made continuous by adjusting the loop length to fit with the seed pulse duration. LSFS configurations can provide pulse trains suitable for wind velocity sensing with T_{pulse} down to 200 ns, a standard $\Delta f = 27.12$ MHz and trains including several hundred pulses. All opto-electronic components are commercially available at 1.55 µm with fiber pigtails.
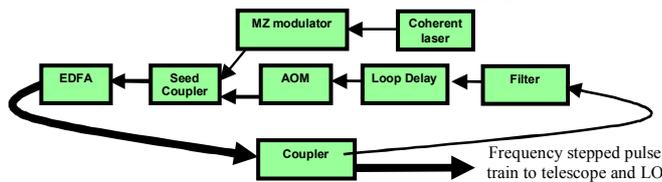

Figure 3: LSFS concept for generating FSPTs.

V. SYSTEM EXAMPLE

The layout of an FSPT modulated coherent lidar can be seen in Fig. 4. To keep power levels low in the LSFS the signal leaving the FSPT generator can be amplified by an external high power EDFA. A LO line can be branched out and possibly delayed in a fiber length and offset in frequency by an AOM. An undelayed, non-offset LO can alternatively be formed from a reflection after the circulator. Such reflections must be avoided for solutions with a separate LO path. The generated beat signal is band pass filtered in accordance with the frequency slots of interest. Sampling of the beat signal is triggered by the LO pulses. The sampled signal is Fourier transformed, some thousand spectra are accumulated and the wind velocity in each range cell is deducted. It might be useful to split the signal and filter out each slot separately, noise will be minimized and it will be possible to undersample each slot at a sampling frequency Δf.
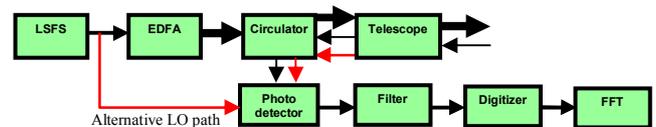

Figure 4 : Layout of an FSPT modulated coherent monostatic lidar. LO in red.

A focused cw system based on a fiber laser and a high power EDFA with an average output power of 1 W and a lens diameter of 7 cm has proven to give reliable wind measurements up to 116 m also for very clear atmospheres [2]. Similar performance is expected of an FSPT modulated lidar with the same average power and optic dimensions. The FSPT lidar would be insensitive to cloud reflections and have improved range resolution for longer ranges. Velocity sensing with an FSPT modified cw system based on the commercial Zephir system is under preparation.

Normalized received energy profiles for the three first range cells of an undelayed collimated FSPT modulated lidar continuously emitting rectangular pulses with $T_{pulse} = 200$ ns can be seen in Fig. 5.
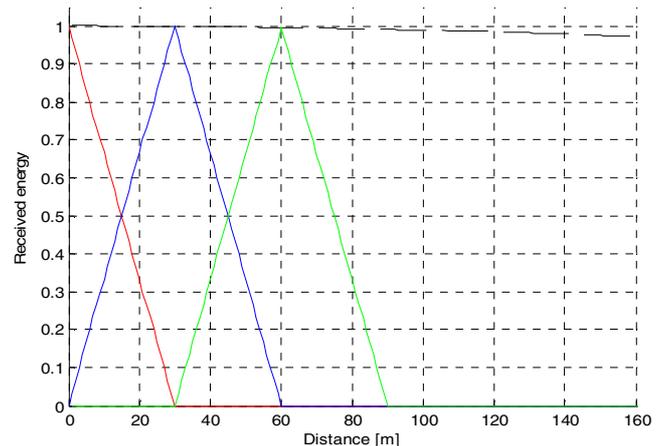

Figure 5: Normalized received energy profiles of the three first range cells of an undelayed collimated FSPT modulated lidar. Range cell one in red, two in blue and three in green. The dashed black line outlines $W_{collimated}(x)$.

The profiles of a cw system and the range cells of an undelayed FSPT-modulated lidar continuously emitting

rectangular pulses with $T_{pulse} = 500$ ns are compared in Fig. 6. The monostatic systems have a telescope radius of 2.12 cm a following Sonnenschein's definition[6]. The focus is set so that the maximum energy is received from 150 m.
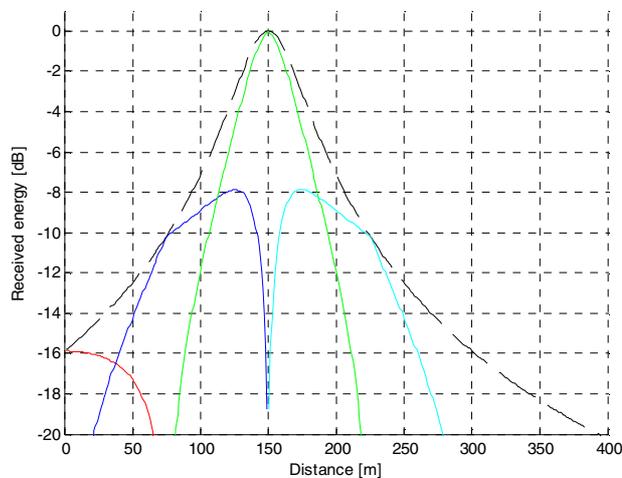

Figure 6: Comparison of the profiles of a cw system (black dahed) and an FSPT modulated lidar continuously emitting rectangular pulses with duration $T_{pulse} = 500$ ns. Range cell one in red, two in blue, three in green and four in cyan. Note that the y-axis is plotted in dB.

VI. CONCLUSIONS

Frequency stepped pulse train modulated lidars have attractive features for range resolved velocity sensing, e.g. of wind velocity. FSPT modulated lidars offer unambiguous range resolved velocity sensing of a dispersed target at high repetition rates. The sensing is unambiguous since scatter from range cells are uniquely mapped into frequency slots. In comparison with focused cw lidars will FSPT-modulated systems be isolated from cloud reflections and have improved range resolution when sensing at longer distances. Possible near term applications are sensing of wind in airports or for evaluation of wind power sites.

The lightwave synthesized frequency sweeper is a suitable FSPT generator. It can in principle emit continuously with stable equidistant frequency steps at fixed intervals. The LSFS can give several hundreds of sub-microsecond pulses before amplified spontaneous emission noise builds up. A 1.55 μm LSFS can be assembled from commercially available fiber pigtailed components.

REFERENCES

[1] G. Pearson and C. Collier, "A pulsed CO_2 lidar for boundary layer meteorology", Q. J. R. Meteorol. Soc. vol. 125, No. 559, pp. 2703-2721 (1999)

[2] D. Smith, M. Harris, A. Coffey, T. Mikkelsen, H. Jørgensen, J. Mann, R. Danielian, "Wind Lidar evaluation at the Danish wind test site in Høvsøre", Wind Energy, vol. 9, No. 1, pp. 87-93 (2006)

[3] C. Karlsson, F. Olsson, D. Letalick, M. Harris, "All-fiber multifunction continuous-wave coherent laser radar at 1.55 μm for range, speed, vibration and wind measurements", Appl. Opt. vol. 39, No. 21, pp. 3716-3726 (2000)

[4] C. Werner, F. Köpp, R. L. Schwiesow, "Influence of clouds and fog on LDA wind measurements", Appl. Opt. vol. 23, No. 15, pp. 2482-2484 (1984)

[5] M. W. Phillips, P. J. M. Suni, J.A. L. Thomson, "Fiber-based LADAR Transceiver for range/Doppler imaging with frequency comb generator", United States Patent 5,835,199 (1998)

[6] C. M. Sonnenschein, F. A. Horrigan "Signal-to-Noise Relationship for Coaxial Systems that Heterodyne Backscatter from the Atmosphere" in Applied Optics, vol. 10, No 7, pp. 1600-1604 (1971)

[7] K. Shimizu, T. Horiguchi, Y. Koyamada, "Frequency translation of light waves by propagation around an optical ring circuit containing a frequency shifter: 1. Experiment.", Appl. Opt. vol. 32, No. 33, pp. 6718-6726 (1993)