Investigation of noise in Lightwave Synthesized Frequency Sweeper seeded LIDAR anemometers from leakage through the Acousto Optic Modulators

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Outline

• Introduction – why LSFS seeded LIDAR?

• Frequency Stepped Pulse Train generator

• Noise in FSPT and wind speed measurements

• Measurement of leakage

• Summary
Introduction

• The LSFS seeded LIDAR transmits a frequency stepped pulse train
• Has been stated to have the potential of combining the high acquisition rate of focused CW systems with the finite sample volume of pulsed systems
  – Continuous in time
  – Pulsed in frequency
• In this work we look at some limiting factors
LSFS seeded LIDAR

![Diagram of LSFS seeded LIDAR system]

- Laser
- EDFA
- LO
- PD
- ESA
- Telescope

Symbols:
- $f'' + 3\Delta f$
- $f'' + 2\Delta f$
- $f'' + \Delta f$
- $f''$
- $f' + 3\Delta f$
- $f' + 2\Delta f$
- $f' + \Delta f$
- $f'$

Parameters:
- $f_{01}$
- $f_{02}$
- $f_{03}$
- $f_{04}$
LSFS seeded LIDAR
LSFS seeded LIDAR
LSFS seeded LIDAR

Laser → EDFA → LO → PD → ESA → Telescope

- $f'' + 3\Delta f$
- $f'' + 2\Delta f$
- $f'' + \Delta f$
- $f''$
- $f' + \Delta f$
- $f' + \Delta f f_{o3}$
LSFS seeded LIDAR

Diagram: Laser → EDFA → LO → PD → ESA → Telescope → R_3 → f' + 2Δf → ±f_{D3} → T' + T_{pulse}
LSFS seeded LIDAR

Laser → EDFA → LO → PD → ESA

Telescope

EDFA

±f_D3

Δf

±f_D3

f' + 2Δf

R_1
LSFS seeded LIDAR
Due to the frequency stepped output and LO signal backscatter from specific range cells are allocated to specific frequency slots in the RF spectrum and backscatter from “old” pulses is not a problem.
Frequency stepped pulse train generator
Frequency stepped pulse train generator
Frequency stepped pulse train generator

The diagram illustrates a frequency stepped pulse train generator setup. It includes a laser (CW), an AOM, a delay, and an EDFA. The process involves a frequency shift ($f_0$) and a delay, leading to a stepped pulse train output ($f_0$).
Frequency stepped pulse train generator
Frequency stepped pulse train generator

![Diagram of frequency stepped pulse train generator]
Frequency stepped pulse train generator

- 10000 revolutions/pulses have been demonstrated (Takesue and Horiguchi, 2004)
- Pulse time down to ~200 ns
Noise in FSPT generator

- Amplified spontaneous emission from EDFA
  - Lot of literature on this subject e.g. Shimizu et al. 1993
- Leakage
  - AOM (seed leakage) – Can be solved by inserting extra AOM
  - AOS (non-shifted) – Builds up as function of revolutions
  - Noise will go to the center of the frequency slots and can limit the LIDAR’s ability to measure low wind speeds
Seed leakage

Optical noise:
\[ P_N^{i+1}(f + \Delta f) = L(f)G^iP_N^i(f) + L(f)P_{ASE}(f) + \varepsilon P_0(f_0) \]

Beat signal noise:
\[ S_N^{j\Delta f}(f) = 2R^2P_0^2\left(\varepsilon + (i - j - 1)\varepsilon^2\right) \]
AOS noise

\[ P_0 \beta \cdot P_0^2 \cdot \beta^2 \cdot P_0^3 \cdot \beta^3 \cdot P_0 \]

\[ P_0 \beta \cdot P_0 \]

\[ P_0 \]

\[ \text{Frequency} \]

\[ \text{Time} \]
AOS noise

\[ P_0 \beta \cdot P_0 \cdot \beta \cdot P_0 \cdot P_0 \beta \cdot P_0 \cdot P_0 \beta \cdot P_0 \]

Diagram showing frequency and time with markers for \( P_0 \) and \( \beta \cdot P_0 \).
AOS noise

\[ P_0 \beta^2 \cdot P_0 \beta \cdot P_0 \]
AOS noise

\[ P_0 \beta \cdot P_0 \beta^2 \cdot P_0 \beta^3 \cdot P_0 \]
AOS noise

\[
\begin{align*}
P_0 & \rightarrow P_0(1+\beta) \\
P_0(1+\beta) & \rightarrow P_0(1+2\beta+\beta^2) \\
P_0(1+2\beta+\beta^2) & \rightarrow P_0(1+3\beta+3\beta^2+\beta^3)
\end{align*}
\]

\[
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 \\
\beta & 1 & 0 & 0 & 0 & 0 \\
\beta^2 & 2\beta & 1 & 0 & 0 & 0 \\
\beta^3 & 3\beta^2 & 3\beta & 1 & 0 & 0 \\
\beta^4 & 4\beta^3 & 6\beta^2 & 4\beta & 1 & 0 \\
\beta^5 & 5\beta^4 & 10\beta^3 & 10\beta^2 & 5\beta & 1
\end{bmatrix}
\]
AOS noise

\[
\begin{align*}
P_0 &

\beta

\begin{pmatrix}
\beta

\begin{pmatrix}
\beta

\begin{pmatrix}
\beta

\begin{pmatrix}
\beta

\end{pmatrix}
\end{pmatrix}
\end{pmatrix}
\end{align*}
\]

Optical noise:

\[
P_{f+1}(f + \Delta f) = (1 - \beta)L(f)[G^i P_N^i(f) + P_{ASE}^i(f)] + \beta L(f)[G^i P_S^i(f_S^i - \Delta f) + G^i P_N^i(f - \Delta f) + P_{ASE}^i(f - \Delta f)]
\]
AOS noise

\[
P_0 \left( 1 + \beta \right) \left( 1 + 2\beta + \beta^2 \right) \left( 1 + 3\beta + 3\beta^2 + \beta^3 \right)
\]

Optical noise:
\[
P_{N}^{i+1}(f + \Delta f) = (1 - \beta)L(f)\left[ G^i P_N^i(f) + P_{\text{ASE}}^i(f) \right] + \beta L(f)\left[ G^i P_s^i(f_s - \Delta f) + G^i P_N^i(f - \Delta f) + P_{\text{ASE}}^i(f - \Delta f) \right]
\]

Beat signal noise:
\[
P_N(i, k) = \frac{i!}{(i-k)!k!} \beta^k P_0
\]

\[
S_N^{i\Delta f} = 2 R^2 P_0^2 \sum_{k=0}^{i} \frac{i!i! \beta^{2k-j}}{(i-k+j)(k-j)(i-k)!k!}
\]
AOS leakage beat signal
AOS leakage beat signal
AOS leakage beat signal
AOS leakage beat signal
AOS leakage beat signal
Leakage measurement

- Setup

![Diagram showing leakage measurement setup](image)
Leakage measurement

• Setup

Laser (1574 nm) → AOS → AOS → PD → ESA

• Results

\[ \beta = -34.9 \text{ dB} \]
Summary

- LSFS seeded LIDARs have the potential of combining the advantages of the traditional wind LIDARs

- Expressions describing the build-up of noise due to AOM and AOS leakage have been derived

- AOS leakage has been measured in a heterodyne setup, but further investigation is necessary