Ultra-low Power Dual-Comb Lidar

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Talk Overview

1. Dual Comb Ranging Background
   • The optical frequency comb source
   • Conventional approach to dual-comb lidar (linear optical sampling)

2. Novel Method of dual-comb ranging detection
   • The time programmable comb
   • Integration into a dual-comb ranging system
   • Results
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The Optical Frequency Comb

A metrology ‘definition’: A femtosecond laser that acts as a ruler in time and frequency

- Broadband, narrow linewidth (Hz-level), few-fs timing jitter when locked
- Used in dual-comb sensing
  - (spectroscopy, imaging, time transfer, 
    ranging)
1) The frequency modes can ‘breathe’
Two-degrees of freedom

Frequency Domain

Time Domain

1) The frequency modes can ‘breathe’
2) The frequency modes can shift

Timing Jitter
To get few-femtosecond timing jitter we need to lock the two degrees of freedom of the comb:

1) Lock to a stable optical reference frequency, $f_{cw}$
2) Lock the carrier envelope offset frequency, $f_0$
Locking the Optical Frequency Comb

We can write the repetition rate:

\[ f_r = \frac{f_{cw} - f_{opt} - f_0}{M} \]

(M is mode number of comb tooth closest to \( f_{cw} \))

\( \sim 3 \) femtosecond timing jitter
Conventional Dual Comb: Linear Optical Sampling

Ranging Signal Comb \( f_{\text{rep}} \)

Local Oscillator Comb \( f_{\text{rep}} + \Delta f_{\text{rep}} \)

\[
\frac{1}{f_r} \propto R(t)
\]

Typical Values for Er:fiber Comb:

\( f_r \sim 200 \text{ MHz} \)
\( \Delta f_r \sim 2 \text{ kHz} \)
We can map ns-level interferogram time shifts $\rightarrow$ fs-level pulse time shifts using magnification factor $\Delta f_r / f_r (\sim 10^5)$.

This gives us 100-nm precision at full update rate (and full power).
# Tradeoffs in Conventional Dual Comb

<table>
<thead>
<tr>
<th>Non-Ambiguity Range</th>
<th>Maximum Update Rate</th>
<th>Deadtime Power Penalty*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{NA} = \frac{c}{2f_r}$</td>
<td>$T^{-1} = \frac{f_r^2}{4B}$</td>
</tr>
</tbody>
</table>

$B = \text{Optical Bandwidth}, f_r = \text{repetition rate}, c = \text{speed of light}$

*Quantifies photons ‘lost’ due to deadtime between linear optical sampling interferogram peaks, how far from shot noise limited.

Lower $f_r$ comb: ↓ Update Rate, ↑ Non-Ambiguity Range, ↓ Power Penalty (Fiber Comb)

Higher $f_r$ comb: ↑ Update Rate, ↓ Non-Ambiguity Range, ↑ Power Penalty (Microresonator Comb)
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*Quantifies photons 'lost' due to deadtime between linear optical sampling interferogram peaks, how far from shot noise limited.*
Tradeoffs in Conventional Dual Comb

Is there a way to break these tradeoffs? Can we have low power, high update dual-comb ranging?

Our Answer: Tracking Dual Comb Ranging
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Stepping Away from Linear Optical Sampling

Linear Optical Sampling Method

- Signal Comb Pulses
- LO Comb Pulses
- Resultant Interferogram

Same number of photons in pulses!

Tracking LO Method

- Signal Comb Pulses
- LO Comb Pulses
- Resultant Interferogram

$1/f_{r,1}$ and $1/f_{r,2}$
Measuring time-of-flight changes

Linear Optical Sampling Method

Tracking LO Method

Signal Comb Pulses

LO Comb Pulses

Resultant Interferogram

\[ \Delta t \]

\[ M\Delta t \]
How do we maintain overlap?

Pulses are only ~600fs wide so target movement of more than 90 μm would cause us to lose signal

**Answer: Time Programmable Frequency Comb (TPFC)**

- **Ranging Signal Comb**
- **TPFC**
- **Command:** move $+\Delta t$
- **Controls**
- **Measure**: $V$

**NEW!**

- Time Programmable Comb

- **Heterodyne Voltage**

- **X(t)**

- **X(t)**

- **NEW!**

- **All the attributes of conventional frequency comb, *plus* programmable agility**

- **NOT freerunning: we know where the comb is throughout the movement**
Timing shifts via Phase Shifts

Time Offset
Command:
\[ \Delta X = 5 \text{ fs} \]
\[ \Delta \theta_0 = \Delta X (2\pi N f_r) = 1 \text{ radian or cycle} \]

Apply Phase Shift

\[ \theta_0 = 2\pi f_0 t \]

\[ +\Delta \theta_0 \]

Digital Electronics

\[ \theta_{opt} = 2\pi f_{opt} t \]
How well can we move the comb?

Time Programmable Frequency Comb (TPFC) $f_{rep}$

Sampling Frequency Comb $f_{rep} + \Delta f_{rep}$
How well can we move the comb?

Time Programmable Frequency Comb (TPFC) \( f_{rep} \)

Sampling Frequency Comb \( f_{rep} + \Delta f_{rep} \)

Time Offset

\[ \text{Time Offset of Time Programmable Comb} \]

\[ \text{Time (1 sec/div)} \]
Nanosecond Agility with Attosecond Accuracy

Time Offset

Time Programmable Frequency Comb (TPFC) $f_{rep}$

Sampling Frequency Comb $f_{rep} + \Delta f_{rep}$

Time Offset Error Statistics:
mean = 0.77 attoseconds (~1 Å)
± standard error = ± 2.05 attoseconds (~3 Å)
Example in Dual-Comb Ranging

Ranging Signal Comb

Time Command

Time Programmable Frequency Comb

Attenuator

Circulator

Optical Timing Discriminator

Servo Controller

Time and Phase Determination

Digital Electronics (FPGA + DSP)

X(t), θ(t)

R(t), V(t) measurements

V_{ch1}

V_{ch2}

Example in Dual-Comb Ranging

FMCW meas.

Reacquisition period after beam blocked

Example in Dual-Comb Ranging

R(t)

V(t) (cm/s)

Power (pW)

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Digital Electronics (FPGA + DSP)
Precision vs Power

Compared to conventional dual-comb ranging with the same frequency combs:

- **40 dB improvement** in minimum received power (down to sub-pW)

- **13x faster** update rate
  
  (26kHz versus 2 kHz)

- All with a **10x improvement** in the high-power precision noise-floor (previous work ~10nm)
Summary

• We show an alternative method of dual-comb lidar using a time programmable frequency comb

• We demonstrate ranging to a moving retroreflector with return powers as low as 3 pW at 26 kHz update rate

• Compared to conventional dual comb ranging with the same combs, this represents a 40 dB improvement in the minimum received power at a 13x faster update rate
Thank You for Listening!

This material is based upon work supported by:

Extra slides follow
1f-2f locking

**offset the carriers of the two combs by ~10 MHz → measure beat note**

**demodulate with 20 kHz BW → 40 kS/sec sampling rate**
Digital Controls