Frequency-Comb Based Approaches to Precision Ranging Laser Radar

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Outline

• Introduction: Combs

• Combs for ranging

• Dual Comb ranging
  – Initial phase-locked system: nm-level precision
  – Simplified free-running system: sub-μm precision in < 1 ms

• Comb-assisted coherent FMCW ranging Ladar
  – Tracking a fast swept laser
  – Preliminary results

• Conclusion
Frequency Comb
Coherent, stabilized femtosecond, mode-locked lasers

2005 Nobel prize to J. Hall & T. Hänsch

Pulse Train

Femtosecond Passively modelocked Laser

Stabilization of any two degrees of freedom → Entire comb stabilized → Entire pulse train stabilized

Frequency Comb (Spectrum)

1/$f_{rep}$

Exact period
Controlled phase

Exact spacing
Controlled offset
Properties of Combs For Ranging

Time-domain

Stable pulse timing $\rightarrow$ time-of-flight
Stable carrier frequency $\rightarrow$ interferometry

Frequency-domain

Comb = thousands to millions of “cw lasers”
with Hz-linewidths and known frequencies
$\rightarrow$ Multi-wavelength interferometry
$\rightarrow$ Calibration of fixed/swept lasers
Different Comb-Based Ranging Systems

“Direct” Comb Ranging

Modulated waveform

Comb

RF phase

Minoshima et al, AO 39, 5512 (2000)

Comb Interferometer

Comb

translate

vary \( f_{\text{rep}} \)

X-correlator

Spectrometer

Joo et al, OE, 14, 5954 (2006)
Cui et al. OE 19, 6549 (2011)
Balling et al, OE 17, 9300 (2009)
Lee et al, NP 4, 716 (2010).

Comb-Assisted Ranging

Multi-Wavelength Interferometer

Comb

\( \lambda_1 \)

\( \lambda_2 \)

\( \lambda_3 \)

Schuhler et al, OL 31, 3101 (2006)
Salvade et al, AO, 47, 2715 (2008)

Dual-Comb Interferometer

Comb 1

Comb 2


FM CW LIDAR

Swept laser

Comb

Processor

Barber et al, OL 36, 1152 (2011).

This work
Dual Comb System in Time Domain: Linear Optical Sampling

Phaselock combs
- Coherent carrier
- Slightly different repetition rate $\Delta f_{rep}$

Source Comb

LO Comb

Interferogram (cross-corr.)

A cross-correlation with timing is as precise as combs

Measurement repeats every $1/\Delta f_{rep}$
Dual-Comb Ranging: Lab Demo

Lab Experiment

Movable Target

Reference

Time-of-Flight Range = \( \frac{v_{\text{group}}}{2} \times \text{time-of-flight} \)

Absolute Range

Interferometric Range = \( \frac{\varphi_T - \varphi_R}{4\pi\lambda} + N\frac{\lambda}{2} \)

ambiguity

Combs phase-locked together
- Coherent carrier
- Precisely offset repetition rate

High-precision Range
Range Uncertainty versus Observation Time

nm-level absolute distance measurements

(Also verified Time-of-Flight and Interferometric Agree)

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< 5 nm at 60 msec

"Range Window" or Ambiguity is 1.5 meters (but can extend to > 30 km)
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Range Uncertainty versus Observation Time
nm-level absolute distance measurements

“Range Window” or Ambiguity is 1.5 meters (but can extend to > 30 km)
Fully Phase-Locked Dual Comb System

- Four phase locks to two cavity-stabilized laser
- Can we trade off precision for simplicity?
  - Nanometer precision excessive for typical terrestrial ranging of \(~10^{-7}\) to \(10^{-8}\) precision

Try a free-running system with no phase locks...
- Interferometric ranging lost
- Time-of-flight ranging still possible?
Free-running Dual Comb System
Time-of-Flight Ranging Without Phase Locks

Free-running rep rate stable to $10^{-8}$ @ 1 sec
Adjust for $\Delta f_{rep} = 7$ kHz between combs
Free-running carrier stable to $\sim$ MHz
Time-of-Flight Ranging with Simpler System
Sub-micron in Sub-milliseconds with 0.75 m range window

- Superior performance (due to higher repetition rate sources)
- Also verified 200 nm linearity across 1 meter
Dual-Comb Ranging

• Advantages
  – Rapid, absolute, high precision ranging (sub-micron in sub-millisecond)
  – Immunity to spurious reflections
  – No significant dead zones

• Disadvantage
  – Inefficient use of photons: Multiplexed disadvantage of $\sqrt{N}$
    10’s of nW to μW return powers (100’s of photons per pulse)

• Suitable for ranging to “cooperative” target with retroreflector
  – Not suitable for diffuse target
  – (True of all direct comb ranging systems….)

Can we combine accuracy of combs with efficiency of FM CW LIDAR?
Combing Swept Cw Lasers & Combs

Tunable diode lasers offer
- ~100 nm tuning ranges
- Rapid scan rates >1000 THz/s in MEMS or Y-branch design
- >10 mW - many Watts and single mode operation.
- Much higher SNR than direct-comb illumination

But
- Optical frequency is poorly defined during sweeps
  (orders of magnitude worse than linewidth)
- Also fastest sweeps will not be linear (but quasi-sinusoidal)

Goal:
- Use frequency combs to track the phase of a swept laser
- With high accuracy
- At high speeds
- Over arbitrary waveforms
Metrology of a Swept CW laser using Frequency Combs

Basic Approach: Heterodyne laser against comb & digitize (fast)

I. Coddington, et al., JSTQE (Invited), IEEE Early Access, (2011)

Dual Comb Spectrometer
- Absolute optical frequency vs time
- Requires dual phase-locked combs
- >1000x faster than wavemeter
- Unique tool for metrology of fast swept lasers

Single Comb Spectrometer
- Relative optical frequency vs time
- Single, free-running comb
- ~20 nanosecond time resolution
- Much higher linearity, speed, flexibility than etalon approaches
Swept CW laser + Dual Comb Spectrometer
Absolute Frequency Determination

\[ f_r \]

Maximum sweep rate (chirp) \( < f_r \Delta f_r = 0.1-1 \text{ THz/s} \) (0.8-8 nm/s)
Swept CW laser + Single Comb Spectrometer

Fast Relative Frequency Determination

Maximum sweep rate (chirp) \( < f_r f_r / 2 = 5,000 \text{ THz/s} (40,000 \text{ nm/s}) \)
Example Measurement of a Fast Swept Laser
MEMS-based ECL

Chirp rates > $10^{15}$/sec
(10,000 nm/sec)

Accuracy ~
30 kHz/μs
(1.5 MHz @ 20 ns)

FM CW Ranging Lab Demonstration
Preliminary Results

>10x faster should be possible
Combs used in many ways for ranging

Direct Dual Comb Ranging system
- Phase-locked system: nanometer absolute ranging at a distance
- Free-running system: sub-micron ranging in < 1 msec at distance
- Multiplexed penalty compared to cw coherent laser radar

Comb-based metrology of swept lasers can track “arbitrary” cw laser waveforms
- Follow waveforms with chirps of few thousand THz/sec
- Absolute or relative frequency measurements

Preliminary comb-assisted FMCW
- Processing intensive
- Range resolution ~ 1/Bandwidth~1 psec ~ 150 microns in 3 msec
- Range precision of 5 microns in 3 msec
- Potential 10x improvement in speed possible….