Spectrally resolved frequency comb interferometry for long distance measurement

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Outline

• Introduction to VSL
• Introduction to the frequency comb
• Many-wavelength interferometry with the fs frequency comb
• Conclusions and outlook
About VSL

- VSL is the national metrology institute of the Netherlands, located in Delft
- Private company with public task
- Turnover: partly government, partly market
- About 100 FTE
- ISO 17025 accredited

VSL is named after Jean Henri van Swinden, who contributed to the development of the meter (end 18th century)
Principle of the frequency comb

- A frequency comb is the spectrum of a pulsed laser:

\[ f_{rep} \]: repetition frequency
\[ f_0 = \phi / 2\pi \] \( f_{rep} \): offset frequentie

\[ f_n = f_0 + n \times f_{rep} \]

Tool for optical frequency measurement
Modelocked pulsed lasers

Many frequencies / ‘modes’ oscillating at same time, phase locked/mode locked:

A pulse train can be viewed as a superposition of phase-locked wavelengths.

Frequency difference subsequent resonant modes:

$$
\Delta f = \frac{c}{2L} = \frac{1}{\text{roundtrip-time}}
$$

$L = 15 \text{ cm} \rightarrow \Delta f = 1 \text{ GHz}$
Pulsed lasers

\[ f = f_a \]
\[ f = f_a + \Delta f \]
\[ f = f_a + 2\Delta f \]
\[ f = f_a + 3\Delta f \]
\[ f = f_a + 4\Delta f \]

And so on, for example 30 waves:

\[ \frac{1}{\Delta f} \]

SUM
Properties of the frequency comb for distance measurement

- Stabilized pulse to pulse distance, acting as a **ruler** for distance measurement
- Wide spectrum, allowing for **spectral interferometry**
- Presence of **thousands** of individual and **stabilized laser modes**, available for homodyne interferometry
Why comb based distance measurement?

– Availability of many stabilized wavelengths
  
  Non-ambiguity range: e.g. 15 cm vs < 500 nm for single wavelength interferometry.
– Prospect of very long range applications (>> 1 km) due to long coherence length
– Direct traceability to SI second

– Potential applications:
  – Absolute distance measurement without displacement
  – Distance measurement between satellites
  – Surveying applications
Distance measurement based on cross-correlation

- Cross-correlation between pulses for path length difference equal to multiple of interpulse-distance.
- Apply model pulse propagation in air
- Compare to helium-neon laser interferometer

1\textsuperscript{st} or 2\textsuperscript{nd} order correlation

Agreement up to 50 m within 1 \(\mu\text{m}\)

Distance measurement based on spectral interferometry

Distance determined from unwrapped phase of spectral interference pattern

\[ S(\omega) = |\hat{E}(\omega)|^2 \left[ 1 + \cos\left(2n(\omega)\omega L / c\right) \right] \]

Distance measurement based on spectral interferometry

• Limitations of spectral interferometry scheme:
  • Applicable to restricted range because of limited resolution of the spectrometer
  • Calibration of wavelength scale needed by using known displacement

• Ultimate goal: ability to resolve (and identify) individual comb modes
  • Allows for measurement of an arbitrary distance, not only close to multiples of $L_{pp}$
  • No indirect calibration needed using known displacement
  • Not only spectral interferometry but also homodyne multi-wavelength interferometry possible.
Unwrapping the comb

- Virtually imaged phase array (VIPA) to create fine angular dispersion (vertical plane)
- **Grating** for rough angular dispersion (horizontal plane)
- Imaging on CCD camera
- **Stitching** of vertical lines to get full frequency scale
Unwrapping the comb

- Comb lines separated into individual dots
- Repetition rate: 1 GHz
- 808-828 nm dispersed in about 9000 unique dots
- VIPA FSR: 50 GHz
Reference wavelength measured with wavemeter with <50 MHz uncertainty
Setup for distance measurement with a VIPA spectrometer

\[ L_{pp} = c/T_{rep} \]

Train of ultrashort pulses

- A typical VIPA measurement
- with delayed arms

(c) Extracting the modulation frequency from the 2D image

Intensity (arb. units)

Number of comb modes
Comb interference at various delays

(a): 33 µm delay distance
(b): 2.5 mm delay distance
(c): 20 mm delay distance
(d): 73.9 mm delay distance
(e): 110 mm delay distance
(f): 147.5 mm delay distance
Reconstructed comb spectrum

- Stitching: 50 dots per vertical line and about 180 lines to get frequency scale with ~9000 comb modes

Delay: 33 μm

Delay: 2.5 mm
Distance determination from spectral interferometry

- Distance is derived from *phase change as function of wavelength*

- Interference \( I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\left(\frac{2\pi \cdot 2L \cdot n}{\lambda}\right) = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\left(\frac{2\pi \cdot 2L \cdot n}{c} f\right) \)

- Phase \( \varphi = \frac{2\pi}{c} 2L \cdot n \cdot f \)

- Determine \( L \) from \( L = \frac{d\varphi}{df} \cdot \frac{c}{4\pi \cdot n} \)
Many-wavelength homodyne interferometry

- For a certain wavelength (dot): determine \( \text{phase} \) from fitted curve
- Determine \( \text{integer number of wavelengths} \) from spectral interferometry
- Determine distance from integer number and phase, applied to known wavelength
- Repeat for 9000 wavelengths and average
- Note: phase determination insensitive to intensity fluctuations
Comparison to counting interferometer

15 cm displacement: Average difference 8 nm, Std. dev 28 nm

Extending the measurement range to 50 m

- Setup of fiber connection to 50 m laboratory
- Optimization of beam expanding optics
- Alignment into high-resolution VIPA spectrometer
- Comparison to counting interferometer
- HeNe laser and comb share the same interferometer
  - Michelson interferometer with polarizing beam splitter
- Installation of single mode DFB laser for wavelength reference (with wavemeter)
Setup
Results

Based on spectral interferometry

\[ \Delta L_{\text{He}} = L_{\text{HeNe}} - L_{\text{Heterodyne_comb}} \]

\[ \Delta L_{\text{He}} \text{ vs. HeNe distance} \]
Conclusions

- Homodyne frequency comb interferometry has been demonstrated for distances up to 50 m
- All distances can be measured, even at maximum pulse separation.
- Exploitations of thousands of comb modes allows for interferometry with huge range of non-ambiguity.
- Agreement with counting HeNe laser within $1 \times 10^{-8}$ at 50 m
- Spectral interferometry and multiwavelength interferometry merged in a single scheme.
- Only one frequency comb needed (compared to heterodyne comb interferometry).
- Interferometer stability in combination with non-perfect synchronization dominates measurement uncertainty
Next steps

- Distance measurement with reduced number of modes
  - Allows for use of fiber-based frequency comb
  - Simpler spectrometer can be used

41 GHz comb VIPA spectrometer
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