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JAHRESTAGUNG 2024

Interferometry for Wireless Networks

Developing Deep Frequency Modulation Interferometry for Optical Sensor Networks

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Introduction

Adopting **scalable compact wireless sensor network** in manufacturing enables the flexibilization in industrial production processes by providing precise, real-time and adaptive responses to structural changes, e.g., the deformation of a curved surface, as part of the dtec.bw project, Digital Sensor-2-Cloud Campus Platform (DS2CCP), with the mutual-reference to the work **"Cyber Physical Finite Element Sensor Network"** by L. -M. Bretthauer et al.

Commercial off-the-shelf (COTS)

Objectives:

- Cost-effective and high precision sensors
  → Optical sensor heads with low-cost COTS laser diode incorporating technique "Deep frequency modulation Interferometry"
- Extending sensing (dynamic) range
  → Evaluation of two types of test masses (TMs) in design aspects
- Error and noise mitigation, caused by laser diodes
  → Investigation on influences such as amplitude modulation(AM) when using distributed feedback (DFB) laser diodes

Deep frequency modulation interferometry

DFMI is an interferometric technique that combines simple geometries of homodyne interferometers with the multi-fringe readout capabilities of heterodyne interferometers by the sinusoidal modulation of the laser frequency injected into an unequal arm length interferometer to generate beat signals [1,2]. The interferometric pattern consisting higher harmonics of the modulation frequency with undesired AM caused by DFB laser diode can be written as:

$$P_{out}(t) = \underbrace{\frac{P_{in}}{2} + \frac{P_{in}}{2} C \cos(\phi + 2\pi\Delta f \tau \cos[\omega_m t + \psi])}_{\text{DFMI signal}} \times \underbrace{(1 + A_{AM} \cos(\omega_m t + \psi_{AM}))}_{\text{AM signal}}$$

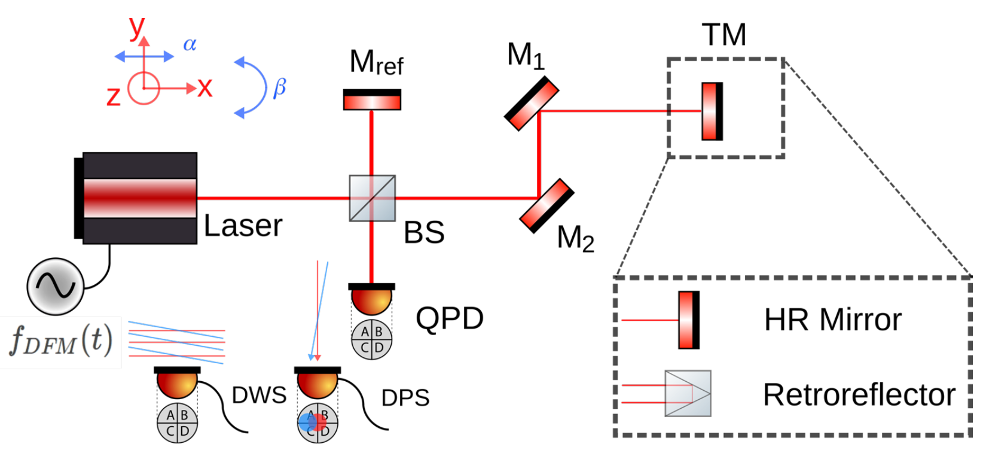
AM disturbed DFMI signal

P_{in} : Laser power on the photodetector
Δf : Applied frequency modulation depth
τ : Time delay between two beams
ω_m : Modulation frequency
ψ : Modulation phase
ϕ : Interferometric phase
A_{AM} : Amplitude modulation strength
ψ_{AM} : Amplitude modulation phase
C : contrast between two beams

The interferometric phase ϕ and the modulation depth $m = 2\pi\Delta f\tau$ are used to measure relative and absolute distances by applying this equation as the time-series fit function.

Interferometer Scheme

- Simple homodyne Michelson interferometer geometry

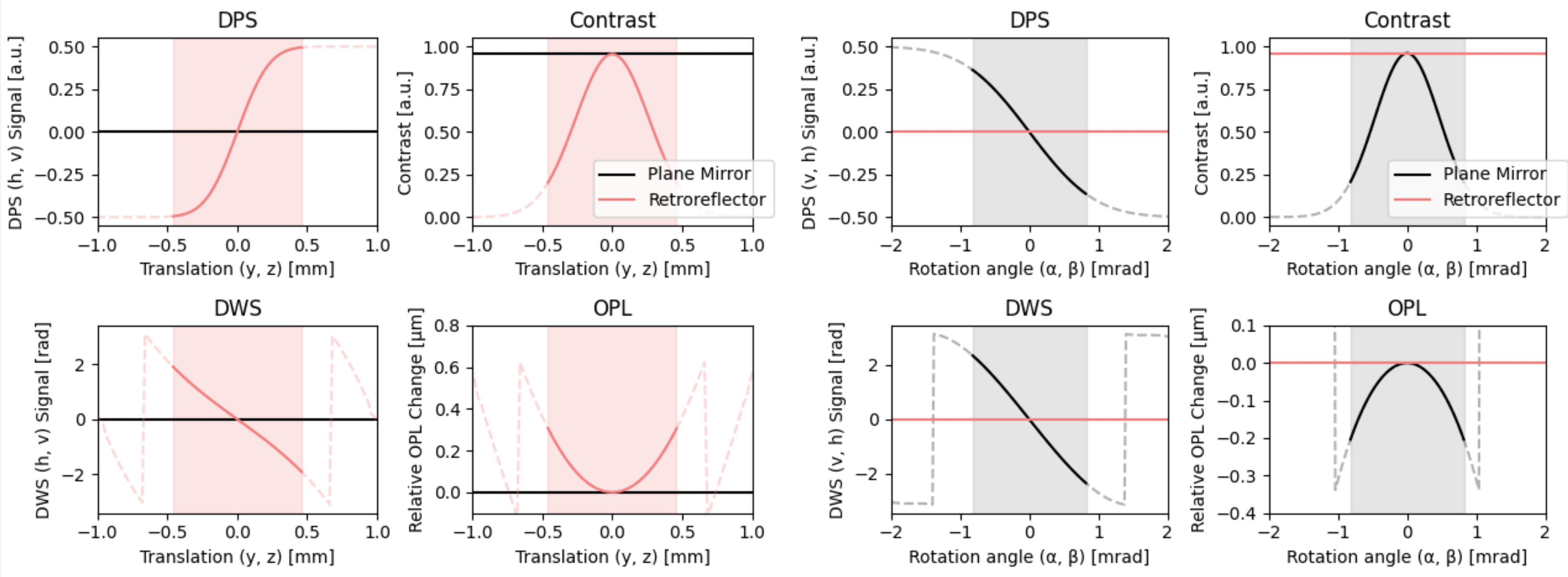


M_x : High reflection mirrors @ 1550 nm
BS : 50:50 Beam splitter
QPD : Quadrant photodiode
Laser : External cavity laser (ECDL, reference), DFB laser diode

- M_1, M_2 are added to match optical axis along the circumference.
- Armlength mismatch of 30 cm
- DPS : Differential power sensing, comparing power signals from the quadrants (left and right, bottom and top) [3]
- DWS: Differential wavefront sensing, comparing relative phase between wavefronts from two interfering beams [3]

Interferometer simulation

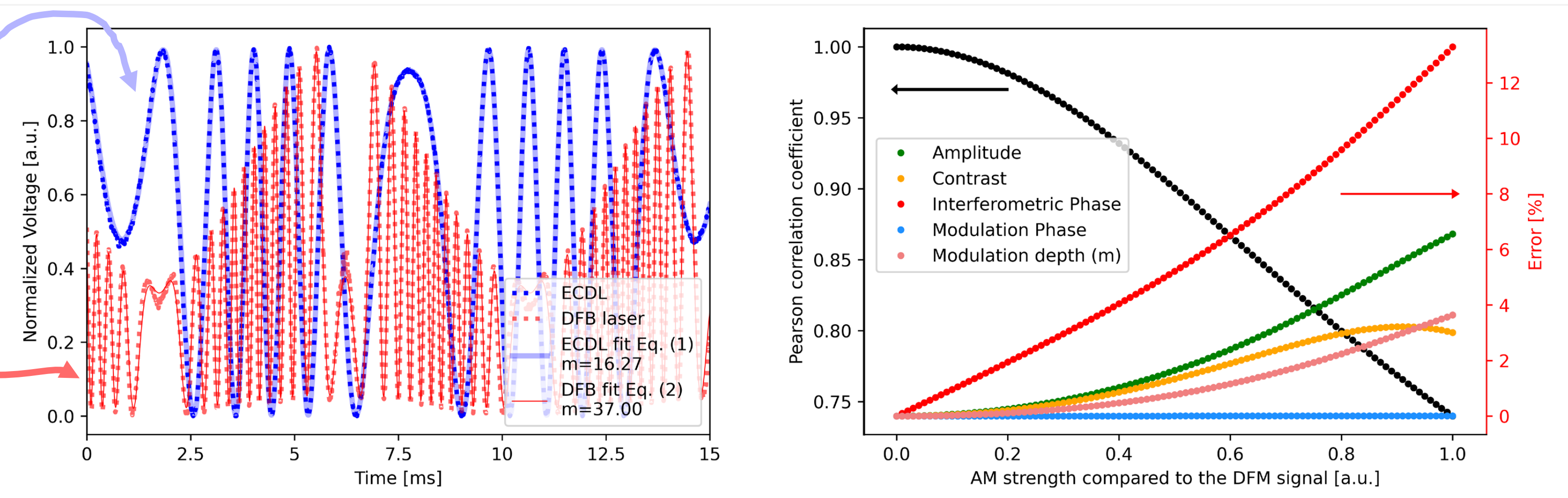
- Simulated ray-traced interferometric signals with tool "IFOCAD"



Test mass	Linear motions (translation) (y-, z-axis)	Rotation (α, β)	Longitudinal Length coupling (x-axis)
Retroreflector	± 0.46 mm	Insensitive	Length-to-length 4.64×10^{-4} mm/mm
Plane Mirror	Insensitive	± 0.82 mrad	Tilt-to-length 2×10^{-1} mm/rad

→ Combination of both test masses could provide five degrees of freedom measurement(x, y, z, α, β) which will be further investigated.

DFMI experiment and simulation



(a) Measured DFMI signals (dots) for ECDL and DFB laser with their fit curves (solid)

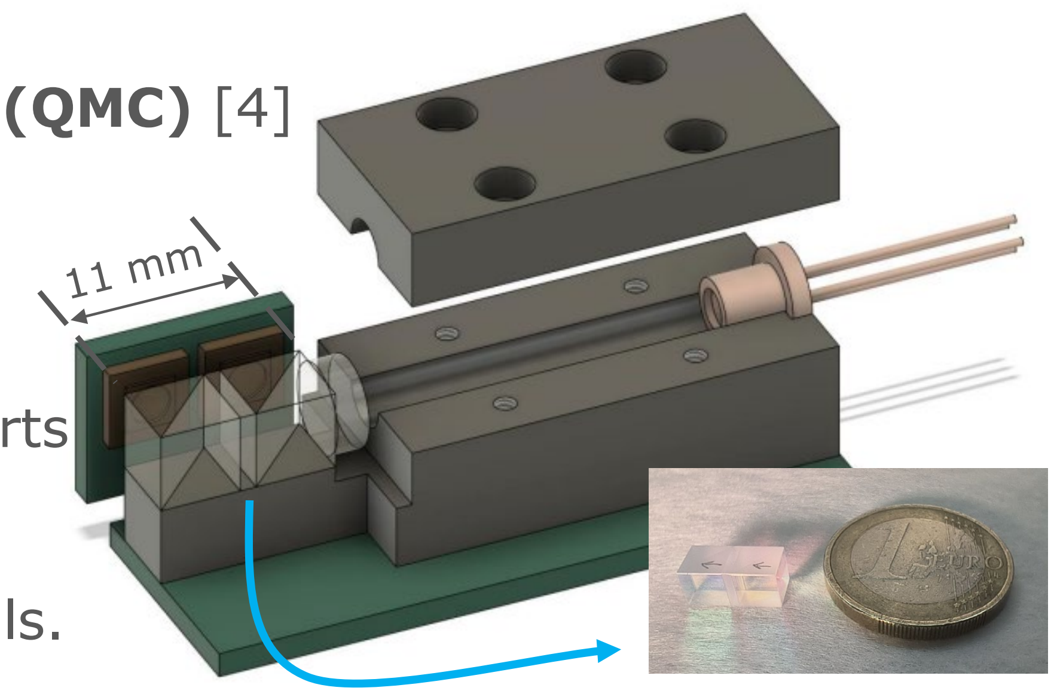
(b) Simulated fit errors (color) and correlation between data and fit curve (black) for residual amplitude modulation

- Amplitude modulation(AM) on top of DFM signal for DFB laser
- Increasing fit parameter errors with incremental AM strength when using DFMI equation as the fit function
- Significant phase errors under the AM (~0.1% error for 1% AM)
- Further investigation of the robustness of other phase extraction algorithms under amplitude modulation will be carried out.

First design outlook of Compact sensor

Advantages of using
Quasi-Monolithic Component(QMC) [4]

- Compact size
- Avoidance of ghost beams
- Avoidance of back-reflection
- Minimal sensor assembly efforts



We will study further on this prototype to explore its potentials.

References

[1] O. Gerberding. "Deep Frequency Modulation Interferometry". DOI:10.1364/OE.23.014753.
[2] K.-S. Isleif et al. "Experimental Demonstration of Deep Frequency Modulation Interferometry". DOI: 10.1364/OE.24.001676.
[3] N. Meshksar et al. "Applying Differential Wave-Front Sensing and Differential Power Sensing for Simultaneous Precise and Wide-Range Test-Mass Rotation Measurements". DOI: 10.3390/s21010164.
[4] O. Gerberding et al. "Ghost Beam Suppression in Deep Frequency Modulation Interferometry for Compact On-Axis Optical Heads". DOI: 10.3390/s21051708

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Digital Sensor-2-Cloud Campus-Platform
gefördert durch
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Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr
Finanziert von der Europäischen Union
NextGenerationEU