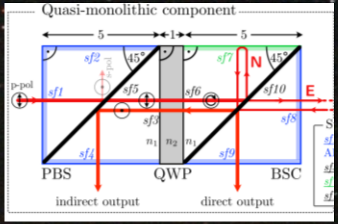
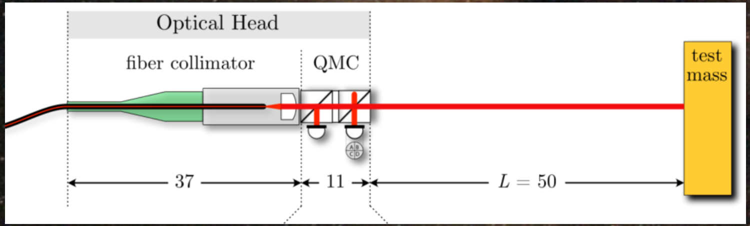
O. GERBERDING, K.-S. ISLEIF

DIGITAL POSTER

GWADW 2021

DEVELOPING AND TESTING COMPACT DISPLACEMENT SENSORS USING DEEP-FREQUENCY MODULATION INTERFEROMETRY





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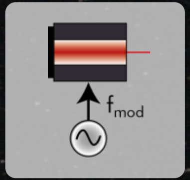
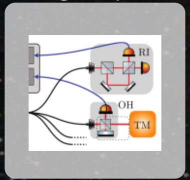
Deep-Frequency Modulation Interferometry (DFMI)

Laser modulation



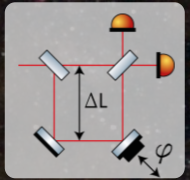
$$f(t) = f_0 + f_\Delta \cos(\omega_m t)$$
$$f_m = 1\,\mathrm{kHz}$$
$$f_\Delta = 3\,\mathrm{GHz}$$

Light split



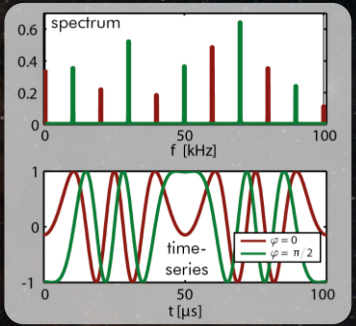
$$f_1(t) = f_2(t) = f_N(t)$$
$$f_R(t) \approx \mathrm{const} + f_\Delta(t)$$

Interferometer

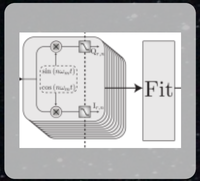


$$L_\Delta = 0.1\,\mathrm{m}$$
$$m = 2\pi \frac{L_\Delta}{c} f_\Delta \approx 7$$

Signal



Phasemeter



$$\hat{i}_{DC}, \hat{i}_{AC}, \hat{m}, \hat{\varphi}, \hat{\psi}$$

power, contrast, ranging, displacement

$$i(t) = i_{DC} + i_{AC} \cos\left(\varphi + m \cos\left(\omega_m t + \psi\right)\right)$$

Main features:

- Signal is inherently non-linear and linearized by the phasemeter algorithm/estimator
- Each interferometer (optical head) has only one input beam and can be very compact
- Laser frequency noise is common mode (can be suppressed actively or in post-processing)
- Provides wide-range sensing of displacement & absolute ranging

O. Gerberding, Optics Express, 23, 11, (2015)
G. Heinzel et al., Optics Express, 18, 19, (2010)
K.-S. Isleif et al., Optics Express, 24, 2, (2016)

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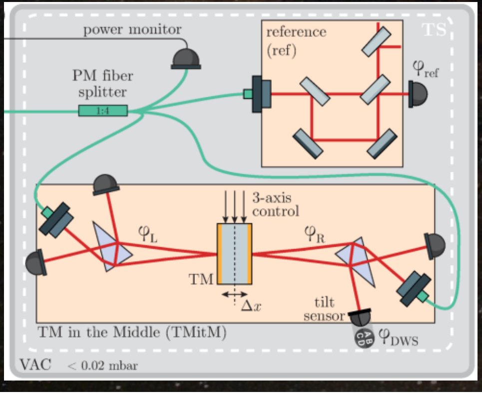
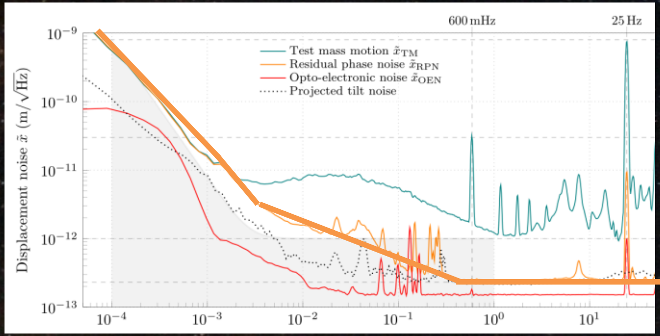
DFMI experimental status

K.-S. Isleif et al., PRApplied 12, 034025 (2019)

Test-mass-in-the-middle experiment with single-component, off-axis topology
- Almost achieved LISA-like performance down to mHz, non-linearity is $<10^{-2}$
- Limited at high frequencies by the phasemeter/ the ADC noise
- We saw some other influences on the noise floor (no good data, but laser modulation SNR a likely candidate)
- At low frequencies fiber polarization and collimator tilt noise dominate (likely not a major issue for LIGO/ET)
- Off-axis design: misalignment during pump-down & limited range (~2mm)





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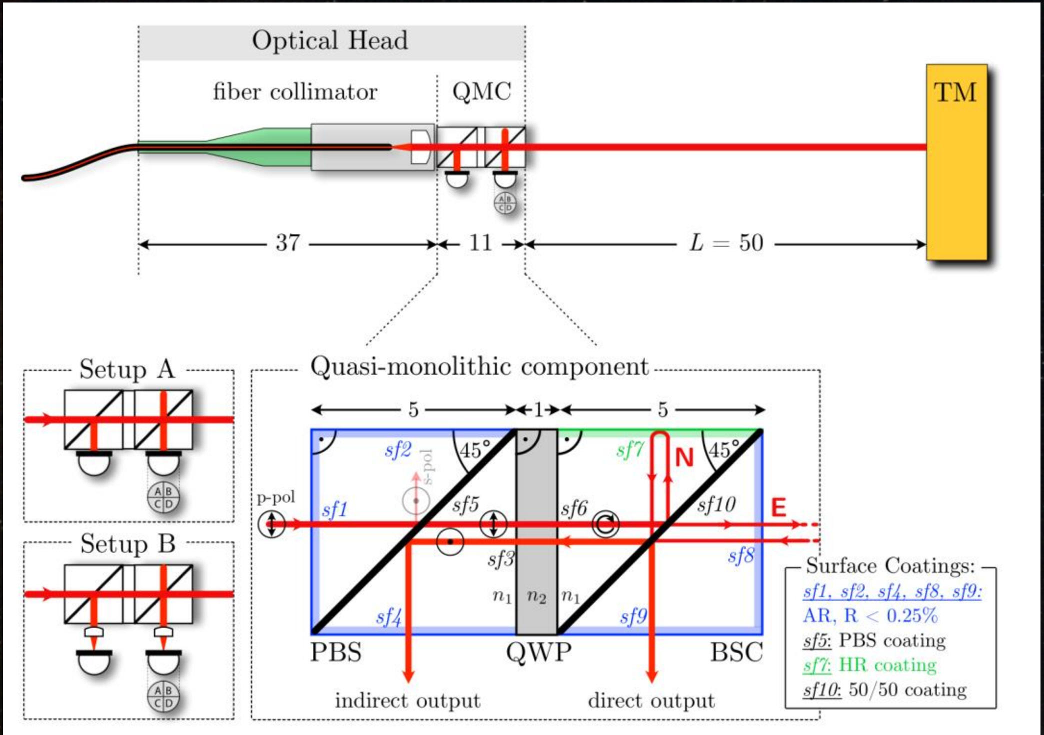
On-Axis Optical Head Design Concept

- Quasi-monolithic component (QMC) establishes unequal arm-length Michelson with no backreflection to the fiber (both output ports accessible)
- Longer longitudinal range than off-axis designs
- No angular alignment change between air and vacuum
- Even smaller optical head designs are possible
- Studied two configurations with and without lenses in front of the PDs



O. Gerberding & K.-S. Isleif, Sensors, 21(5), (2021)

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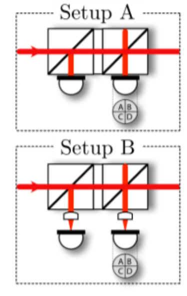
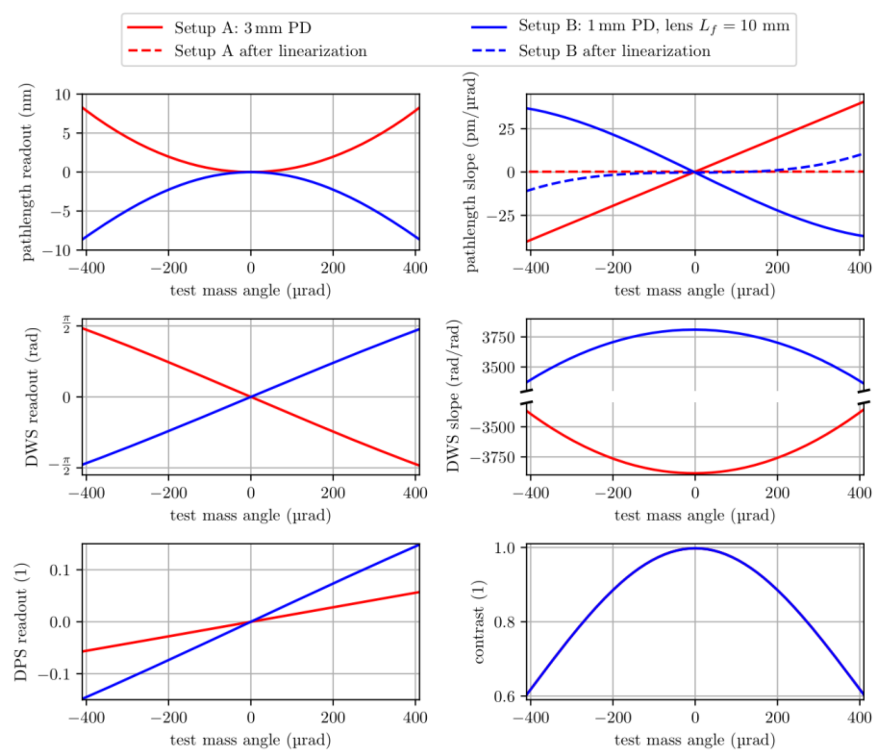
On-Axis Optical Head Simulation via IfoCAD

- Simulated the dependencies of pathlength, contrast, differential power and wavefront sensing on test mass tilt with IfoCAD
- Assumed an input beam with 1mm waist diameter and a nominal distance of 5cm to the test mass
- Imaging optics:
  - Without a focusing lens (Setup A) the nominal tilt-to-pathlength coupling is large, but highly linear
  - This means we can use the DWS signals to correct and mount PDs close to the QMC





O. Gerberding & K.-S. Isleif, Sensors, 21(5), (2021)

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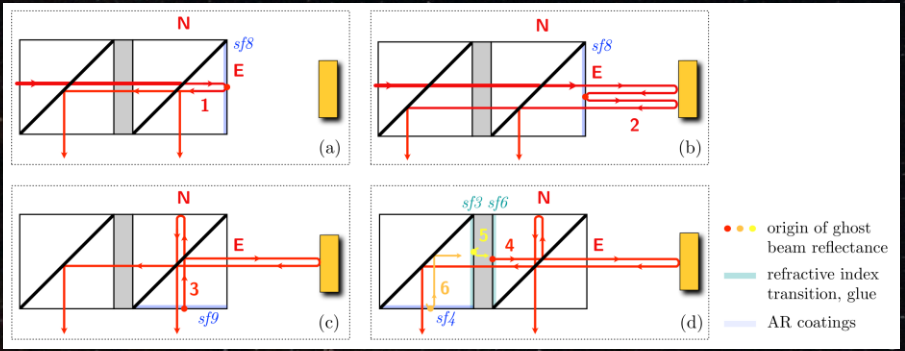
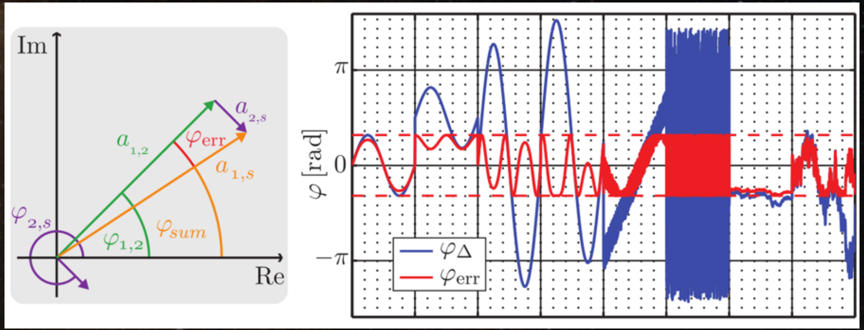
Ghost beams

- On-axis designs suffer from ghost beams due to
  - AR coated surfaces
  - Bonding surfaces (depens on the bonding method and the refractive index of the materials)
- Parasitic interferometers can create non-linear phase noise
  - Since the QMC is „stable“ this will mostly impact the linearity of the phase readout
- Parasitic coupling is in principle rather well understood for homodyne and heterodyne interferometry, but DFMI is different!





O. Gerberding & K.-S. Isleif, Sensors, 21(5), (2021)

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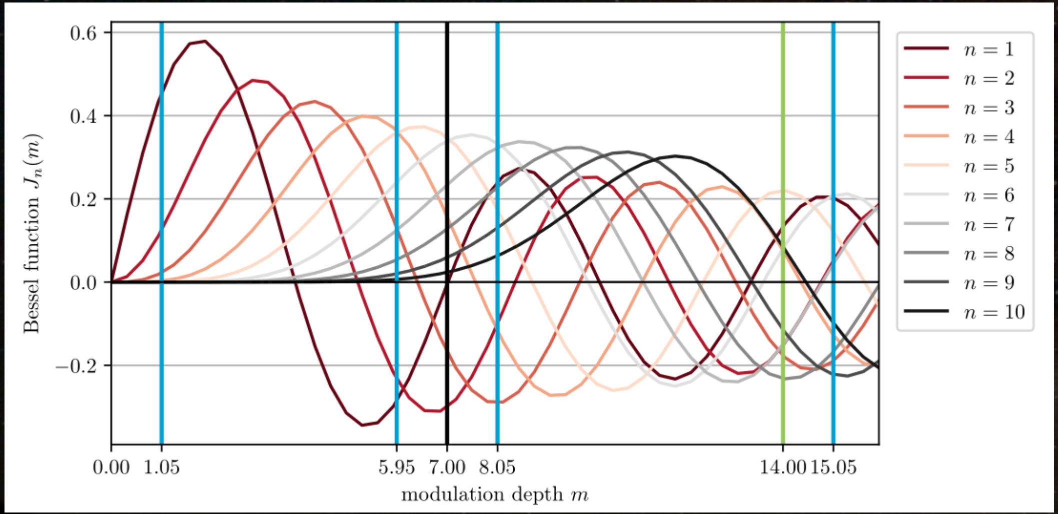
In DFMI different propagation delays create signals that are to some degree orthogonal. We can modify the readout algorithm to account for this to reduce the influence of beat notes with other propagation delays. We have demonstrated this in simulations and achieved a non-linearity below 0.1%.



$$
\begin{aligned}
P^{\pm}_{\mathrm{N,E},1,2} = & \pm E_{\mathrm{N}} E_{\mathrm{E}} \cos\left[\phi_{\mathrm{E}} + m_{\mathrm{E}} c(t)\right] \\
& \pm E_{\mathrm{N}} E_1 \cos\left[\phi_1 + m_1 c(t)\right] \\
& \pm E_{\mathrm{N}} E_2 \cos\left[2\phi_{\mathrm{L}} + \phi_1 + (2m_{\mathrm{L}} + m_1) c(t)\right] \\
& + E_{\mathrm{E}} E_1 \cos\left[\phi_{\mathrm{L}} + m_{\mathrm{L}} c(t)\right] \\
& + E_{\mathrm{E}} E_2 \cos\left[\phi_{\mathrm{L}} + m_{\mathrm{L}} c(t)\right] \\
& + E_1 E_2 \cos\left[2\phi_{\mathrm{L}} + 2m_{\mathrm{L}} c(t)\right] \\
= & \pm 1 \cos\left[\phi_{\mathrm{E}} + m_{\mathrm{E}} c(t)\right]
\end{aligned}
$$

n = 2... $\pm 0.05 \cos\left[\phi_1 + m_1 c(t)\right]$

2m fit $\pm 0.05 \cos\left[2\phi_{\mathrm{E}} - \phi_1 + (2m_{\mathrm{L}} + m_1) c(t)\right]$

BD $+0.05 \cos\left[\phi_{\mathrm{E}} - \phi_1 + m_{\mathrm{L}} c(t)\right]$

BD $+0.05 \cos\left[\phi_{\mathrm{E}} - \phi_1 + m_{\mathrm{L}} c(t)\right]$

$+0.0025 \cos\left[2\phi_{\mathrm{E}} - 2\phi_1 + 2m_{\mathrm{L}} c(t)\right]$

O. Gerberding & K.-S. Isleif, Sensors, 21(5), (2021)

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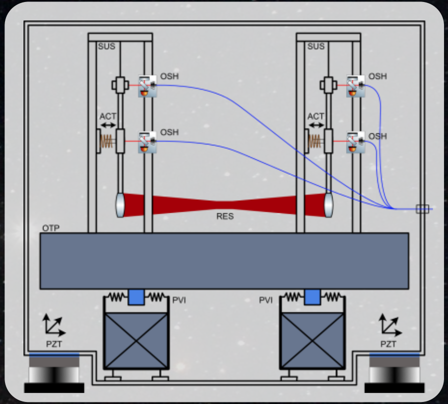
DFMI sensor outlook



Samples of the QMC are available and we are about to test it in the lab.

Our goal is to test the DFMI sensors on suspensions that we will start to design towards the end of the year.

The suspensions will be placed in a seismically isolated vacuum system / inertial testbed that we are currently procuring.