Partially-levitated membranes for high-frequency gravitational wave detection

Ultra-high frequency gravitational wave workshop

CERN, December 5, 2023

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Mechanical membrane oscillators / resonators

Silicon nitride (SiN) membrane (typically 10 to 100 nm thick) [1]

\[ f_{mn} = \frac{1}{2\ell} \sqrt{\frac{\sigma}{\rho} (m^2 + n^2)} \]

Mechanical stress: \( \sigma = 1 \text{ GPa} \)
Mass density: \( \rho = 3000 \text{ kg/m}^3 \)

Partial optical leviation

- Straight-forward installation of membrane chip inside cavity
- Optical standing wave inside cavity provides a harmonic potential for membrane → optical spring constant [2]

\[ k_{\text{opt}} = \frac{d^2 U_{\text{opt}}}{dx^2} = \frac{16\pi \mathcal{P} |r|}{\lambda c |t|} \]

- Membrane’s oscillation frequency depends on optical power

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Optical trapping of mechanical thin-film oscillator

Optical trapping of glass pendulum [3]

Detector sensitivity

Ultra-high-vacuum: pressure \( \sim 10^{-11} \) mbar (mechanical \( Q \sim 10^{13} \))

Strain sensitivity on resonance: 
\[
h \approx \frac{4}{L} \left[ k_B \frac{T}{m(2\pi f_{GW})^3 Q} \right]^{1/2}
\]

Predicted sensitivity & signals

Goal: similar sensitivity to Levitated Sensor Detector [5] (Andrew Geraci’s talk this morning):

Evolution of mechanical thin-film oscillators

Images (left to right):
Ghadimi et al., Science (2018)
Bereyhi et al., Nature Comm. (2022)
Bereyhi et al., Phys. Rev. X (2022)
Pratt et al., Phys. Rev. X (2023)

| Partially-levitated membranes for high-frequency gravitational wave detection | Christoph Reinhardt, 05.12.2023 | DESY
Phononic crystal PnC membrane

Photo of PnC membrane chip [6]

Simulated mode profile of 1st defect mode

Mechanical quality factor scales with $\ell^2$:

$$Q = \xi \frac{\ell^2 \sigma}{d^2 E_2}$$

Geometry  Material Parameters

$\ell \sim 3$ cm, Si instead of SiN $\Rightarrow Q > 10^{12}$

Tunability of defect mode up to factor 2 [8]:

$\Rightarrow$ cover frequency range from 30 kHz to 300 kHz with 5 PnC membranes

Towards a prototype detector

Goal: table-top prototype

- Meter-scale optical cavities
- cm² scale membranes made out of crystalline silicon with $Q > 10^{12}$
- Cryogenically cooled to 10 K
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Huang, et al., arXiv:2309.15051 (2023)
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Current status & possible next steps

• Submitted grant application to develop membranes for HFGW detection, together with Albert Schliesser’s group (Niels Bohr Institute) and Benno Willke’s group (Albert Einstein Institute)

• Working towards grant application for prototype detector

• Current ALPS II / cryoplatform infrastructure could enable a cryogenic 100-m-scale experiment

• Available expertise at DESY: optics, control systems vacuum, cryogenics, nanoparticles / levitated-nanoparticles and on partially-levitated membranes

ALPS II / cryoplatform infrastructure at DESY

See Axel Lindner’s talk tomorrow 15:30

Synergies: membrane pressure sensor [9]

Together with Roman Schnabel’s group (University of Hamburg)

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Thank you

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