Ultrastable Lasers
New Developments and Challenges

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Progress of cavity-stabilized lasers

- room-temperature glass cavities
- cryogenic cavities

10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13}

Stanford
MPQ
Uni Konstanz
NIST
JILA
SYRTE
MPQ
NPL
JILA
PTB
JILA/NIST
PTB/NIST
PTB/JPB
PTB/JILA
JILA/PTB

21 cm silicon @ 124 K
48 cm ULE
6 cm silicon @ 4 K
1 \times 10^{-17}?

Transportable 1400 nm Sr clock laser

fused-silica mirror substrates

20 cm ULE glass spacer

crystalline AlGaAs/GaAs mirror coatings

acceleration sensitivity:
$3(3) \times 10^{-11}$/$g$

Cryogenic silicon optical resonator

Silicon spacer
dielectric mirror coatings
• $L = 212$ mm
• $T = 124$ K
zero thermal expansion
Cryogenic silicon optical resonator

Two systems with dielectric coatings

- $L = 212 \text{ mm}$
- $T = 124 \text{ K}$
- Stability limited by thermal noise to $4 \times 10^{-17}$
- Si3 moved to JILA in 2017

Flywheel for an optical timescale

Demonstration of a Timescale Based on a Stable Optical Carrier

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- daily measurements to Sr-lattice clock with 25 % uptime
- estimated error < 150 ps over one month

Cavity drift in June 2023:
-48 µHz/s
-4.1 Hz/day
at 1542 nm
(abut 1000 times less than ULE)
Brownian Noise in Fabry-Perot Cavities

High-finesse optical cavity

Fluctuation-dissipation theorem relates length fluctuations to mechanical loss $\phi_x$

$$S_x \propto \frac{T \cdot \phi_x}{f}$$

$$\sigma_y^2 = 2 \ln(2) \cdot \frac{S_x(1 \text{ Hz})}{L^2}$$

thermal noise for a 20 cm long cavity:

$$\sigma_y = 2.5 \times 10^{-16}$$

thermal noise reduction:

- go to low temperatures $T$
- enlarge cavity length $L$
- enlarge mode diameter
- choose low loss material $\phi_x$

AlGaAs crystalline mirror coatings

Cavity length: \( L = 212 \text{ mm} \)
Mirrors: 2x plano-concave (2 m ROC)
Finesse: 380 000 at 124 K
Free Spectral Range: 707 MHz
Birefringent mode splitting: 200 kHz
Thermal noise: \( \text{mod} \, \sigma_v(\tau) = 1 \times 10^{-17} \)

Cole et al., Nat. Phot. 7 (2013) 644

GaAs/AlGaAs DBR disc
silicon substrate

coating: \( n_{\text{slow}} > n_{\text{fast}} \)
Novel noise contributions at low temperatures

**light-modified birefringence**
- non-thermal, light-induced change of cavity resonance
- different sign for fast and slow axis
- time constant of many hours!

**birefringent noise**
- even with stabilized laser power
- anticorrelated in fast and slow axis
- correlation length < mode diameter
- so far only observed at 4K, 16K, 124K

**global excess noise**
- remaining noise when averaging birefringent noise
- exceeds Brownian thermal noise
- correlation length > mode diameter

\[ \Delta n_{\text{stat}} \approx 10^{-4} \quad \Delta n_{\text{photo}} \approx 10^{-8} \quad \Delta n_{\text{noise}} \approx 10^{-10} \]
Novel noise contributions at low temperatures

light-modified birefringence

- non-thermal, light-induced change of cavity resonance
- different sign for fast and slow axis
- time constant of many hours!

Possible explanation:
Light is exciting carriers in the AlGaAs / GaAs semiconductor building up electric field along the coating?

linear electro-optic effect?

\[ \Delta n \approx r_{41} n_0^3 E \]

- electro-optic tensor component \( r_{41} = 1.5 \, \text{pm/V} \)
- refractive index GaAs \( n_0 \approx 3.48 \)

\[ E \approx 3 \, \text{kV/m} \]

small compared to electric field strengths in heterojunctions

\[ \Delta n_{\text{stat}} \approx 10^{-4} \quad \Delta n_{\text{photo}} \approx 10^{-8} \]

Measurements at 124 K and 4 K

JILA 6 cm Si cavity at 4 K

PTB 21 cm Si cavity at 124 K

Birefringent noise
1/f excess noise
Non-thermal
Stability at 124 K

- Birefringent noise can be removed with polarization averaging
- The remaining frequency stability \( \sigma_y \approx 4 \times 10^{-17} \) is still higher than predicted thermal noise

Origin of remaining noise:
- Brownian thermal noise?
- \( \varphi(124 \text{ K}) \gg \varphi(300 \text{ K}) \)?
- Other unidentified noise?
Spatial noise correlation on mirror

- Local noise $l_{corr} \ll w$
- Global noise $l_{corr} \gg w$

- Coating Brownian thermal noise
- Birefringent noise
- Cavity temperature fluctuation
- Vibrations
- Thermo-optic noise ($\tau > 1$ s)
- etc.
Measurement of Brownian thermal noise
Brownian thermal noise

Determine upper limit of coating Brownian thermal noise

<table>
<thead>
<tr>
<th>Mode</th>
<th>HG(_{00})</th>
<th>HG(_{01})</th>
<th>HG(<em>{00}-HG</em>{01})</th>
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</thead>
<tbody>
<tr>
<td>Integration profile</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
<td><img src="image3.png" alt="Graph" /></td>
</tr>
<tr>
<td>Scaling of mod (\sigma_y)</td>
<td>1</td>
<td>(\sqrt{0.75})</td>
<td>(\sqrt{0.75})</td>
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<tr>
<td>Predicted noise level</td>
<td>(\text{mod } \sigma_{y00} = 1.0 \times 10^{-17})</td>
<td>(\text{mod } \sigma_{y01} = 0.86 \times 10^{-17})</td>
<td>(\text{mod } \sigma_{y\Delta} = 0.86 \times 10^{-17})</td>
</tr>
<tr>
<td>Measured/calculated</td>
<td>(\text{mod } \sigma_{y00} = 0.97 \times 10^{-17})</td>
<td>(\text{mod } \sigma_{y01} = 0.84 \times 10^{-17})</td>
<td>(\text{mod } \sigma_{y\Delta} = 0.84 \times 10^{-17})</td>
</tr>
</tbody>
</table>

\(\varphi(124 \text{ K}) \approx \varphi(300 \text{ K})\)
Further investigations at room temperature

48 cm ULE cavity with AlGaAs mirror coatings at room temperature.
Sensitivity to external light

\[ \Delta \nu \propto \ln(I + I_0) \]

- 450(10) nm, \( \kappa = 1 \)
- 625(7) nm, \( \kappa = 3 \)
- 525(13) nm, \( \kappa = 5 \)
- 890(22) nm, \( \kappa = 6.5 \)

Fused Silica

\( \Delta n(I_{\text{ext}}) \)

38.5 layer pairs

GaAs (115.6 nm)

Al\(_{0.92}\)Ga\(_{0.08}\)As (133.2 nm)

LED
Wavelength-dependent sensitivity

![Graph showing wavelength-dependent sensitivity](image)

- **GaAs** (115.6 nm)
- **Al$_{0.92}$Ga$_{0.08}$As** (133.2 nm)

Delta refractive index ($\Delta n (I_{exr})$) for 38.5 layer pairs.

Fractional sensitivity (arb. u.) for LED.
EMPIR – European Metrology Programme

cryogenic cavities, e.g.
10 mK closed-cycle dilution cryostat
12 kg silicon spacer @ FEMTO-ST

spectral holes

vibration isolation

nanostructured mirrors

large modes
Nanostructured mirrors

Meta-Etalon mirror

- combine grating $R_1 \approx 99.9\%$ with rear dielectric mirror $R_2 \approx 99.9\%$
- thermal noise is mostly determined by silicon grating
- $\sigma_y = 4 \times 10^{-18}$ @ 124 K possible

First results of cavity with one meta-etalon:

- Finesse 12 000
- $R \approx 99.95\%$

S. Dickmann et al. Commun. Phys. 6, 16 (2023)
Large mode area cavities

Larger mode size:
smaller averaged thermal coating noise

<table>
<thead>
<tr>
<th>R_1 (m)</th>
<th>R_2 (plane)</th>
<th>rel. σ_y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>plane</td>
<td>1.00</td>
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<tr>
<td>2</td>
<td>plane</td>
<td>0.84</td>
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<td>plane</td>
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<tr>
<td>20</td>
<td>plane</td>
<td>0.47</td>
</tr>
<tr>
<td>50</td>
<td>plane</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Problems:
mirror manufacturing
cavity assembly, tolerances:
mode shifts 1 mm for 10 arcsec deviation

Large modes
at the edge of stability

\[ g_2 = 1 - \frac{L}{R_2} \]
\[ g_1 = 1 - \frac{L}{R_1} \]
Transportable 124 K Si system

- Cool cavity to 124 K by circulating cold gas between pulse tube cooler and cavity environment
- Lock cavity during transport
Summary

- silicon cavities at 124 K with dielectric coating reach thermal noise limit instability of $4 \times 10^{-17}$
- crystalline coatings so far do not provide lower instability

Outlook

- low-noise nanostructured meta-etalons $F \approx 12\,000$
- operation at 4 K
- transportable systems

Funding
Replace the open loop LN2 system by a He-gas cooled, closed-cycle cooling to get a stand-alone and low-maintenance system.

**drawbacks:**

- LN2 infrastructure needed
- about 400 liters LN2/week needed
- two refills per week (holidays, X-mas ...)

about 10 W cooling power needed
124 K Cryostat

Active shield
Passive shield
Cooled Nitrogen gas feeding lines
Vacuum chamber
Silicon cavity
Ion getter pump

required vibration sensitivity
\[ \Delta L/L < 10^{-10} / \text{ms}^2 \]

T. Kessler et al., Nature Phot. 6, 687-692 (2012)

vertical vibration noise
\[ S^{1/2} \approx 5 \cdot 10^{-6} \text{ms}^2/\text{Hz}^{1/2} \]

temperature fluctuations
\[ \alpha_{Si} (T_0 - 50 \text{ mK}) < 1 \cdot 10^{-9} \text{ K}^{-1} \]

mod \[ \sigma_T (K) \]

averaging time (s)

\[ 10^{-10} \]
\[ 10^{-8} \]
\[ 10^{-6} \]
\[ 10^{-4} \]
\[ 10^{-2} \]
\[ 10^0 \]
\[ 10^1 \]
\[ 10^2 \]
\[ 10^3 \]
\[ 10^4 \]
\[ 10^5 \]
Long-term drift

Cavity frequencies vs. H-Maser

- Long-term frequency drift
  \[ \sim 4 \text{ Hz/day} \quad - 2.4 \times 10^{-19}/\text{s} \]
  about $10^3$ times smaller than ultralow expansion materials at room temperature

- less than Hubble constant
  \[ H_0 = 2.27 \times 10^{-18}/\text{s} \]

- June 2023:
  -48 \mu Hz/s
  -4.1 Hz/day

492 days in vacuum

- 09.10.2015
- 29.01.2018

- 492 days in vacuum
- 06.05.2016
- 09.10.2015

- 06.05.2016
- 09.10.2015
Parasitic Etalons

light is fed back to cavity mode with parasitic reflectivity \( R_p = r_p^2 \)

field changes mirror reflectivity (as seen from inside the cavity):

\[
E_r = r E_{\text{in}}
\]
to

\[
E_r = (r + tr_p t e^{i\phi})E_{\text{in}}
\]

\[
\delta \phi = t^2 r_p \sin(\phi)
\]

\[
\delta \nu \approx \frac{1}{2} r_p \sin(\phi) \Delta \nu_{\text{FWHM}}
\]

Periodic frequency fluctuation related to air pressure

Parasitic etalons

Model: \( \Delta p \rightarrow \Delta n \rightarrow \Delta \phi \rightarrow \delta \nu \)

\( R_p = 1.2 \times 10^{-6}, L = 0.41 \text{ m} \)

optimized: \( R_p < 5 \times 10^{-8} \)
Thermal-noise Zoo

- **Brownian (thermal) noise:** internal friction in coating, mirror, spacer
- **Thermo-elastic:** thermal expansion from temperature fluctuations
- **Thermo-refractive:** refractive index change from temperature fluctuations
- many more ...

M. L. Gorodetsky

Thermal noise $S_x(f)$ for fused silica mirror with SiO$_2$ / Ta$_2$O$_5$ coating at 300 K
$\lambda = 1542$ nm, $w = 400$ µm
Evaluation of technical noise

All technical noise sources are suppressed to below $10^{-17}$

- residual amplitude modulation (RAM)
- vibrations with additional low frequency servo loop
- ....
All thermal noise contributions are proportional to mechanical loss factor $f$:

- 0.6 µW
- 0.8 µW

Unlock for 20 min

200 kHz
Transient response – power dependence

So far no simple explanation
- semiconductor properties?
- electric fields from internal photoeffect?
- electrooptic/photorefractive effect?

Further investigations necessary:
- temperature
- spatial correlations
- relation to noise
• Ultrahigh reflectivity: combine grating $R_1 \approx 99.9\%$ + rear dielectric mirror $R_2 \approx 99.9\%$

• Thermal noise mostly determined by silicon grating - $\sigma_y = 4 \times 10^{-18}$ @ 124 K possible

Goals:

Stand-alone system (towards field use)

Reduce impact of by vibrations by additional feedback on AVI and feedforward technique (WP2)
He-based closed cycle cryostat

- Cryo system from TransMIT arrived at PTB
- Check cooling performance and vibration level on test system.
- Replace LN2-based cooling system of Si5 (124 K, 21 cm silicon, AlGaAs coatings)
Crystaline AlGaAs / GaAs multilayer

- Low optical absorption and scatter (A+S < 16 ppm)
- Lower mechanical loss than dielectric coatings

Reduced Brownian Thermal Noise

\[
\phi_{\text{SiO}_2/\text{Ta}_2\text{O}_5} \approx 5 \times 10^{-4}
\]

\[
\phi_{\text{AlGaAs}} \approx 2.5 \times 10^{-5}
\]

F = 400 000
\(\delta \nu = 1.8 \text{ kHz}\)

F = 290 000
\(\delta \nu = 8.6 \text{ kHz}\)

PTB (21 cm)
124 K

JILA (6 cm)
4 K
Birefringent noise – power dependence

![Graph showing birefringent noise dependence on power for different powers and frequencies.](image)

**Equation:**

- $P_{\text{intra}} = 0.37W$
- $1/f^{1.5}$
- $P_{\text{intra}} = 2.02W$
- $P_{\text{intra}} = 0.21W$
- $P_{\text{intra}} = 0.09W$
- $1/f$
- $1/f^{2.5}$

**References:**

- D. Kedar et al., Optica 10, 464 (2023)  
  [https://doi.org/10.1364/OPTICA.479462](https://doi.org/10.1364/OPTICA.479462)
- J. Yu, et. al., arXiv:2210.15671 [physics.optics]  
  [https://doi.org/10.48550/ARXIV.2210.15671](https://doi.org/10.48550/ARXIV.2210.15671)
The excess noise:

- Long correlation length
- $1/f$ slope in PSD
- Independent of optical power
Change of splitting by intracavity power

\[ \Delta n (l_{\text{cavity}}) \]

\[ \Delta n = \frac{38.5 \text{ layer pairs}}{w_0 = 0.5 \text{ mm}} \]

GaAs (115.6 nm)

Al_{0.92}Ga_{0.08}As (133.2 nm)

\[ w_0 = 0.5 \text{ mm} \]

\[ \Delta n \propto \ln(l + l_0) \]

\[ \Delta n \propto l^{0.4} \]