Ultrastable lasers for precision spectroscopy

N. Zhadnov [a,b], K. Kudeyarov [a,b], D. Kryuchkov [a,b], I. Semerikov [a,b], K. Khabarova [a,b], N. Kolachevsky [a,b]

[a] P.N. Lebedev Physical Institute, Moscow, Leninsky prospekt 53, Russia

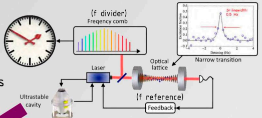
[b] Russian Quantum Center, Skolkovo, Moscow region, Russia

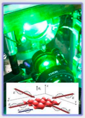
Intro to precision frequency measurements

"Never measure anything, but frequency!"- Arthur Schawlow

Why?
- Measuring frequency is simply counting and measuring time
- Using higher frequencies leads to higher precision
- Heterodyne detection → easy to compare with etalons

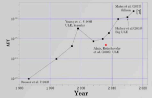
Optical atomic/single-ion clocks





Tm lattice clocks

Ultrastable lasers



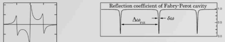
≈ order of magnitude increase in every 10 years

- ▶ Probing narrow clock transition
- ▶ Providing stability on times <100 sec

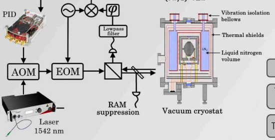
Applications

- Global navigation systems
- Detecting variation of fine-structure constant in time
- General relativity tests
- Topological defects detection

PDH locking scheme



$$r_{FP}(\Delta\omega) = -\frac{\Delta\omega(\Delta\omega+i\delta\omega/2)}{(\delta\omega/2)^2+\Delta\omega^2},\ \Delta\omega \ll \Delta\omega_{FSR}$$



Silicon cryo- cavities

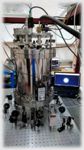
Monocrystalline silicon (for spacer & substrate)
- ‣ Transparent at λ > 1200 nm`
- ‣ High Young's modulus (3x for Quarts)
- ‣ High thermal conductivity (100x for glass)
- ‣ Zero CTE point at 124 K
- ‣ Very low mechanical losses (φ≈10^{-8})

Alternatives: **ULE glass, sapphire, zerodur, fused silica, GaAs (?).**

Mirror coatings:

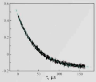
Multilayer Bragg reflectors made from SiO_2/Ta_2O_5 (dielectric) or AlGaAs/GaAs (crystalline). Both have excellent optical properties, but crystalline mirrors are more promising due to higher resistance to thermal noise. They also demonstrate birefringence.

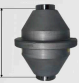
Real setup:
- ▸ vacuum 10^{-9} mbar
- ▸ 3 mK temperature stab.
- ▸ Autonomous LN2 generator



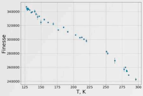
GaAs/AlGaAs multilayer Bragg reflectors

SiO_2/Ta_2O_5
Finesse≈580000





AlGaAs/GaAs
Finesse≈250000

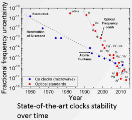


Sources of noise

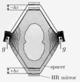
$$\frac{\delta f}{f} = -\frac{\delta\tilde{L}}{\tilde{L}}$$

f – optical mode frequency
$\tilde{L}$ – generalized cavity length

Source	Remedy
Vibrations	Insensitive resonator mount
Temperature instability	Stabilizing temperature at zero CTE point
Thermal noise	High-Q materials (Silicon substrates, GaAs mirrors)
Thermal noise	Lower temperatures (up to 4 K with Silicon)
Thermal noise	Longer cavities



State-of-the-art clocks stability over time

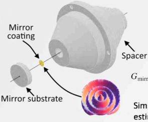


Cavity support in vertical configuration

Thermal noise

$$G_{spacer}(f) = \frac{2k_BT}{f}\frac{L}{3\pi^2R^2E}\phi_{spacer}$$

Thermally induced vibrations of the surface lead to fluctuations of length and eigen-frequency



$$G_x(f) = -\frac{2k_BT}{\pi f}\cdot\Im[H(f)] \quad H(f) \equiv \frac{\tilde{X}(f)}{\tilde{F}(f)}$$

Levins method: $2\pi f\Im[H(f)] = \frac{2W_{diss}}{F_0^2}$

[2]

$$G_{mirror}(f) = \frac{2k_BT}{f}\frac{1-\sigma^2}{\pi^{3/2}Ew_0}\left(\phi_{sub} + \frac{2}{\sqrt{\pi}}\frac{1-2\sigma}{1-\sigma}\frac{d}{w_0}\phi_{coat}\right)$$

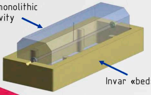
Simplified formula for estimation of thermal noise floor:

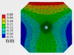
$$\sigma_y \sim \frac{\sqrt{T\cdot\varphi_{coat}}}{L^{5/4}\cdot\lambda^{1/2}\cdot E^{1/2}}$$

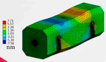
Spacer/ substrate	Mirror	Contribution of substrate, %	Contribution of coating, %	$\sigma_y \cdot 10^{-17}$
ULE/SiO_2 (77.5 mm)	SiO_2/Ta_2O_5	1	97	49
Si/Si (77.5 mm)	SiO_2/Ta_2O_5	<1	99	22
Si/Si (77.5 mm)	AlGaAs	3	97	5
ULE/SiO_2 (480 mm)	AlGaAs	1	88	7

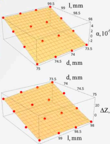
FEA to find optimal support strategy and vibrational sensitivity

Horizontal cavity mount:



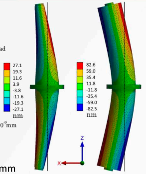






l = 98.68 mm
d = 74.46 mm

Horizontal and vertical long cavities



$$\frac{\Delta\tilde{L}}{\tilde{L}} = \bar{s}\cdot\bar{a}, \bar{s} = \overline{s^T} + \overline{s^R}$$

Vibration sensitivity	Vertical cavity, 1/g	Horizontal cavity, 1/g
s_X^R	2×10^{-8}	2×10^{-10}
s_X^T	2×10^{-8}	1×10^{-10}
s_Y^R	2×10^{-8}	4×10^{-11}
s_Y^T	2×10^{-8}	4×10^{-11}
s_Z^R	8×10^{-12}	2×10^{-10}
s_Z^T	1×10^{-10}	3×10^{-10}

References

[1] D. Matei et al. Phys. Rev. Lett. 118, 263202 (2017)

[2] K. Numata et al. Phys. Rev. Lett. 93, 250602 (2004)

RQC Russian Quantum Center