Optical properties of a silicon ultrastable cavity with crystalline mirrors

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Abstract. We investigated optical properties of a silicon cavity with GaAs/AlGaAs crystalline mirrors that are used to reduce thermal noise level. Cavity finesse was found to be $3.47 \times 10^5$ at the temperature of 127 K. Birefringence of mirror coatings leads to emergence of separate TEM00 modes for two orthogonal polarizations of light. Results of the research indicate that such cavity at cryogenic temperature is suitable for laser frequency stabilization.

1. Introduction
Today a lot of scientific and technological fields, such as metrology, spectroscopy, astronomy and navigation, require laser systems with stable radiation frequency. Moreover, an ultrastable laser with narrow linewidth is an essential part of modern optical clocks and its performance can limit the clock stability [1].

The most widespread way of laser frequency stabilization is locking to an eigenmode of a high-finesse Fabry-Perot optical cavity, especially via Pound-Drever-Hall (PDH) method [2]. In this case the stability of laser is determined by the variation of distance between mirrors (which can be caused by various environmental perturbations: temperature fluctuations [3], vibrations, etc.) and by imperfections in optoelectronic feedback loop (such as residual amplitude modulation instability [4]). The fundamental limit of frequency stability is imposed by thermal noise of cavity spacer, mirror substrates and coatings. To lower the thermal noise limit, one needs to properly design cavity geometry and choose materials with high mechanical Q-factor [5]. The most prominent material for ultrastable reference cavities is monocrystalline silicon. Very high Q-factor of silicon ($10^8$) and low temperature of zero CTE point (124 K) reduce the level of thermal noise. State-of-the-art laser locked to 212-mm silicon cavity yields fractional frequency instability of $4 \times 10^{-17}$ on averaging times of 1-100 s [6].

Such superb level of stability is not easy to reproduce, but a single laser locked to a silicon cavity can serve as a universal local oscillator. Its stability can be transferred to any laser source in the lab with the help of a femtosecond frequency comb [7] while experiments in a distant laboratory can be supplied with stable laser radiation using dissemination over fiber and open-air links [8, 9].

2. Silicon cavity with crystalline mirrors
Thermal noise level of the cavity with spacer and mirror substrates made of silicon is limited by mechanical Q-factor of thin multilayer reflective coatings (see table 1). The loss angle of dielectric Bragg mirror ($\text{SiO}_2/\text{Ta}_2\text{O}_5$) $\varphi_{\text{diel}} = 4 \times 10^{-4}$ is much greater than that of silicon ($\varphi_{\text{Si}} = 10^{-8}$). In order to further reduce frequency instability the novel design of reflective coatings is required. A lot of materials were proposed to substitute traditional layers: amorphous silicon [9], $\text{SiO}_2:\text{HfO}_2$ [11], $\text{Ta}_2\text{O}_5:\text{TiO}_2$ [12], but they improve the coatings mechanical Q-factor only by a small amount. This obstacle was overcome by the creation of crystalline GaAs/AlGaAs coatings that have $\varphi_{\text{cryst}} = 2.5 \times 10^{-5}$ and are supposed to provide both much lower thermal noise and good reflectance [13].

| Cavity part                  | Fractional frequency instability by thermal noise, $\times 10^{-17}$ |
|-----------------------------|-------------------------------------------------|
| Silicon spacer              | 0.0003                                          |
| Silicon substrates          | 0.03                                            |
| $\text{SiO}_2/\text{Ta}_2\text{O}_5$ coatings | 21.9                                           |
| GaAs/AlGaAs coatings        | 5.3                                             |

**Figure 1.** Silicon cavity with crystalline mirrors.

3. Experiment
There are several precision spectroscopy experiments in LPI including optical clocks on thulium atoms [14] and ytterbium ion [15], so creation of a universal local oscillator with low frequency instability would be fruitful. We have constructed a 77.5 mm long cavity of biconical shape (figure 1). Both mirror surfaces are spherical and have 1 meter radius of curvature. Mirrors are fixed on the cavity body via optical contact bonding. Estimated fractional frequency instability caused by thermal noise is $5.3 \times 10^{-17}$.

To investigate optical features of constructed silicon cavity we have repeatedly measured its finesse by ringdown during the process of cooling from room temperature to the silicon zero CTE point of 124 K. Cooling was conducted in a vacuum cryostat, filled with liquid nitrogen, described in [16]. Although mirror coatings were designed to have peak reflectance at a wavelength of 1550 nm, initial experiment was conducted with the use of 1542 nm laser. We expected no significant difference due to wide reflectance plateau around central wavelength [12]. However, cavity finesse was increasing linearly
during the cooling and reached the value of $3.47(3) \times 10^5$ (that corresponds to reflectance of 0.999991) at 127 K (figure 2).

![Figure 2](image)

**Figure 2.** Finesse dependence on cavity temperature. Each point is an averaged over four measurements. Cavity temperature was recovered from thermal shields temperature data according to the model described in [3].

After we got access to 1550 nm laser, measurement of cavity finesse was repeated and yielded the value of $3.00(2) \times 10^5$ with no significant finesse variation during the cooling process. We attribute previously obtained temperature dependence to slight variation of reflectance spectrum due to thermal expansion. Near the central wavelength (1550 nm) reflectance could be perfectly flat, but going 8 nm apart a small slope could emerge. Thermal contraction of Bragg mirrors makes them more suitable for shorter wavelengths and could be one of the reasons for the increase in finesse with decrease of temperature at 1542 nm.

Another feature of GaAs/AlGaAs mirrors that should be taken into account during laser stabilization is birefringence. Changing the polarization axis of the incident light we obtained a pair of TEM00 cavity eigenmodes with a separation of 145 kHz. It is much larger than cavity linewidth (approximately 5 kHz) so we were able to lock laser to particular mode using conventional PDH method with circular light polarization, but it should be investigated whether the presence of second mode has any impact on frequency stability.

4. Conclusion
We have constructed a silicon optical cavity with crystalline mirrors and measured its finesse in the cryogenic to room temperature range. Reflectance of these mirrors at cryogenic temperature turned out to be suitable for ultrastable laser system which we are working on.

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