Development of a Sub-Kelvin Silicon Cavity

J. Barbarat, J. Gillot, J. Millo, C. Lacroûte, V.Giordano, and Y. Kersalé
Femto-St, Université de Bourgogne-Franche-Comté, CNRS, ENSMM
26, rue de l'Epitaphe, 25000 Besançon, France
joannes.barbarat@femto-st.fr

T. Legero
Physikalisch-Technische Bundesanstalt
Bundesallee 100, 38116 Braunschweig, Germany

We report a pathfinder to address the current limitations of ultrastable lasers based on optical Fabry-Perot cavities, aiming to set the ground for the next generation targeting frequency instabilities below 1×10^{-17}. This pathfinder proposes to frequency stabilize a 1.5 µm laser to a silicon Fabry-Perot cavity with crystalline $Al_{0.92}Ga_{0.08}As/GaAs$ mirror coatings at sub-Kelvin temperature. This temperature is reached by using cryogenic dilution refrigerator.

Keywords— Fabry-Perot cavity – Optical frequency standard – Sub-kelvin – cryogen dilution.

I. Introduction

Lasers stabilized to ultrastable optical cavities are required both for the development of more advanced devices and for the widespread applications like spectroscopy, gravitational waves detectors, spectroscopy, frequency standard and tests of fundamental physics [1].

Typically, silicon cavities are operated at temperatures that correspond to the zero-crossing points at 124 K and 17 K where the silicon thermal expansion coefficient vanishes, and the impact of temperature fluctuations is greatly reduced. The cryogenic temperatures strongly improve the frequency stability by reducing the limiting Brownian thermal noise of the cavity [2] [3]. It is also possible to use temperatures below 4 K, where the silicon thermal expansion asymptotically approaches zero. Lower temperature is expected to reduce thermal noise-limited frequency instability [4]. However, silicon cavities with crystalline mirror coatings at cryogenic temperatures have shown birefringence correlated frequency fluctuations [5], [6]. Following this path, we propose to explore and characterize the behaviour of a silicon cavity in that temperature range.

II. METHODS

The spacer of the cavity is made from a monocrystalline silicon with optical axis aligned to the [111] axis. The size of the cylindrical spacer is about 18 cm in length and 20 cm in diameter. Mirrors with silicon substrates and $Al_{0.92}Ga_{0.08}As/GaAs$ crystalline coatings are optically contacted [7]. The mirrors are centered and the crystalline orientation is matched to the spacer using a mask (Fig. 1).

The design of the AlGaAs multilayer is optimized for operation at cryogenic temperatures. The assembled cavity (Fig. 2) shows a finesse of about 220 000 at room temperature (Fig. 3). The TEM00 mode splitting due to the birefringence of the coatings will be quantified.

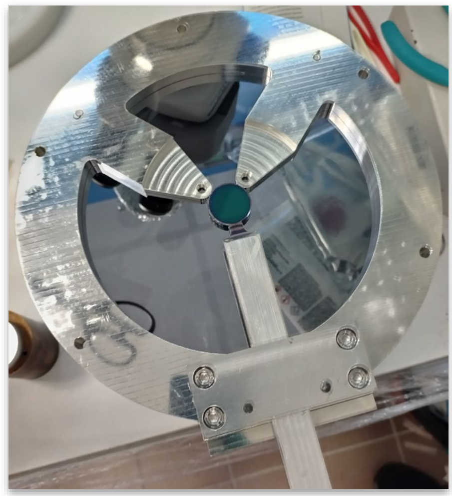

Fig. 1 – A mask was used to ensure the centering and proper alignment of the miroirs with the crystalline spacer orientation.

To reach a sub-Kelvin range, the cavity is placed in a cryogenic refrigerator based on a pulsed tube system in addition to a dilution stage. When the system is unloaded and equipped with optical access, a minimal temperature of 14 mK is measured. The housing of the cavity (Fig. 4) is designed to get a stable support of the cavity in three contact points and to maximize heat exchange by thermal conduction since radiative exchange becomes weak for the targeted temperature range due to the temperature dependancy.

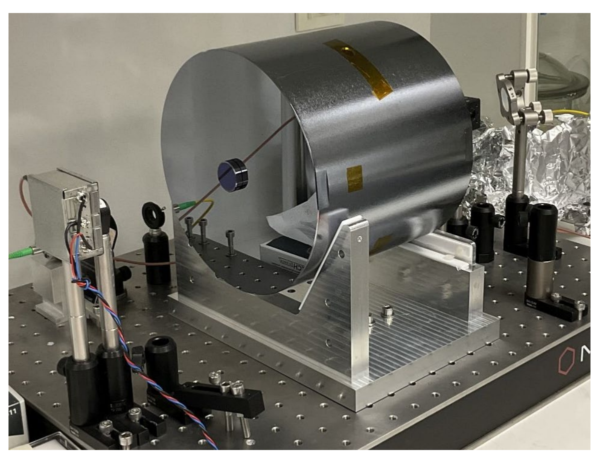

Fig. 2 – View of the assembled silicon cavity

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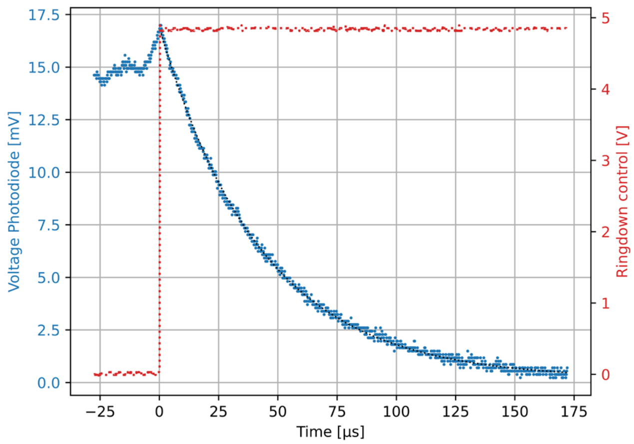

Fig. 3 – Two finesse measurement by the ring-down method. A $\tau = 42 \pm 2$ µs is measured that corresponds to a finesse $F = \frac{\tau\pi c}{L}$ giving F = 220 000 ± 10 000.

This low temperature frequency reference will be used to stabilize the frequency of a laser source using the Pound-Drever-Hall technique [8] giving access to its properties such as finesse, temperature sensitivity or laser power sensitivity.

III. Discussion

The pathfinder must investigate novel approaches to efficiently decouple temperature fluctuations and vibrations intrinsic to the closed-cycle continuous cryogenic operation of an optical cavity at sub-kelvin, leasing the mechanical support. The room-temperature measurement of the cavity finesse and birefringence-splitting will be reference points for our study. Mechanical and thermal managements should allow us to reach the sub-kelvin range.

IV. Conclusions

We propose a pathfinder to measure optical characteristics of a silicon cavity with crystalline AlGaAs coatings at sub-kelvin temperatures, as well as the sensitivity of the silicon cavity to residual temperature fluctuations in the cryostat. We also investigate the efficiency of the cavity cooling at sub-kelvin.

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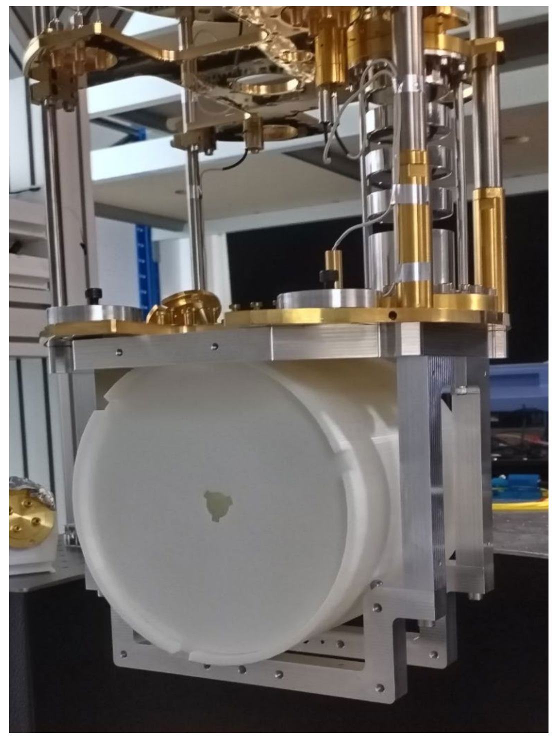

Fig. 4 – Test of the mechanical support with a dummy cavity. The support holds the cavity in three contact points. The support is attached to the coldest plate of the cryogenic dilution refrigerator.