Toward an Ultra-Stable Laser Based on Cryogenic Silicon Cavity

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***Abstract*—We present the development of an ultra-stable laser based on a Fabry-Perot cavity made from single crystal silicon. This cavity is cooled down to 17 K to reach a nulling of the thermal expansion. Thanks to the high mechanical quality factor of silicon and to the low temperature, the expected thermal noise limited fractional frequency instability is 3×10^{-17}.**

I. INTRODUCTION

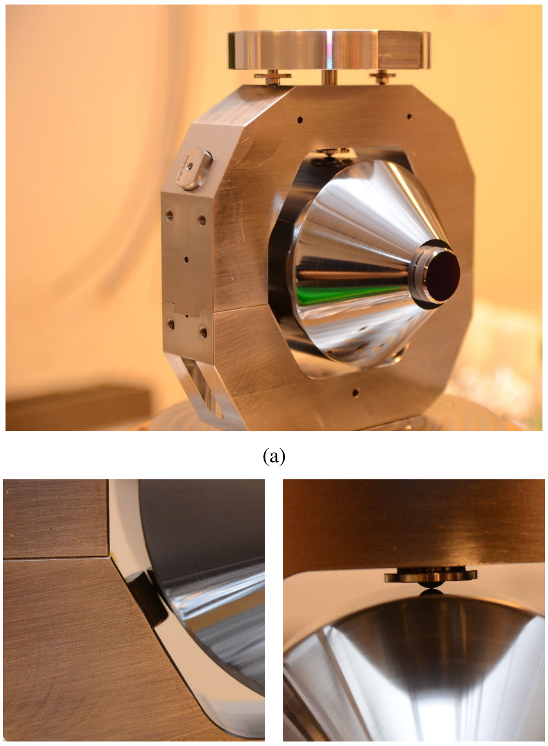
Ultra-stable lasers based on high finesse Fabry-Perot cavity are currently the most stable atomic-transition-free frequency reference [1] and are thus widely used as local oscillators in optical frequency standards [2]. The frequency stability of these lasers is limited by the length fluctuations of the cavity. One can also point out the vibrations-induced deformation and the thermal noise which are the most challenging issues for the improvement of cavities [3].

In order to reduce the thermal noise, we use a monocrystalline silicon cavity to take advantage of its high mechanical quality factor compared to ULE glass or fused silica. The coefficient of thermal expansion of silicon vanishes for two temperatures 17 K and 124 K [4]. Since the thermal noise scales with the temperature (in terms of power spectrum density), we choose to operate the cavity at the lowest of these two temperatures using a cryocooler. For a cavity with a length of 140 mm, this noise limits the frequency stability at 3×10^{-17} in fractional value. However, the cryocooler is based on a pulsed tube, which is a large source of seismic noise and requires a design of the cavity with a state-of-the-art vibration sensitivity with the strong constrain of the cryogenic environment.

II. SILICON CAVITY

The horizontally-oriented optical axis of the cavity is perpendicular to the $\langle 111 \rangle$ plane of the crystalline structure which presents the largest stiffness. The cavity is held in three points included in its $\langle 111 \rangle$ middle plane (see Fig. 1(a)) and the maintaining forces are aligned to specific orientations of the crystalline structure. The simulated sensitivity is about 4.5×10^{-12} $(\mathrm{m.s}^{-2})^{-1}$ or better for each direction.

To keep the support independent of the temperature (varying from 300 K to 17 K), the upper contact point is placed under a mass of about 1 kg. The contacts areas are reduced by using a sphere (on the top) and two cylinders made from stainless steel (see Fig. 1(b) and 1(c)).



(a)

(b) (c)

Fig. 1. 140 mm long silicon cavity (a) with tapered ends held in the support with three contact points (b, c).

III. CRYCOOLER AND MECHANICAL SETUP

With the expected vibration sensitivity of the cavity, the acceleration noise must stand below -110 dB $(\mathrm{m.s}^{-2})^2$/Hz at 1 Hz. To meet this specification, a low vibration cryocooler based on a pulsed tube cryogenerator (PT410, Cryomech) has been designed.

The reduction of the vibration level is obtained by minimizing the mechanical coupling between the pulsed tube and the cavity. The head of the pulsed tube is linked to the ground by a rigid frame while the vacuum vessel of the cryocooler is set on an optical breadboard with an active isolation of vibrations. Only two weak mechanical links are needed. The first one is a bellows placed between the head

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and the vessel. The second one is a link realized by soft copper braids between the pulsed tube and the experimental part to ensure the extraction of the heat. This experimental part containing the cavity, the support, the thermal shield and the regulation stage is directly set to the bottom of the vacuum chamber through supports with low thermal conductivity.

IV. TEMPERATURE REGULATION

The temperature of the colder stage of the pulsed tube is 4.2 K after 15 days of cooling. Due to the limited conductivity of copper braid, the equilibrium temperature of the experimental part is at 4.5 K with typically 15 mK short term fluctuations (peak to peak value in few Hertz bandwidth). Using a set of four heating resistances fixed on about 8 kg of copper, the temperature of a thermal shield is regulated around 17 K with a stability below 0.2 mK (estimated with Allan deviation) between 1 s and 10^4 s. The short term is limited by the noise of the sensor and the long term by the influence of the temperature of the laboratory.

V. OPTICAL SETUP

The optical set-up is depicted in Fig. 2. On a first optical table (TABLE 1), there are the tunable laser source at 1550 nm to match the transparency of silicon, the acousto and electro-optic modulators used for the frequency control with a large bandwidth (AOM1 and EOM1). A first Michelson interferometer is needed to measure and compensate the noise of the fiber link, detected on PD1, to the active vibration isolated table (TABLE 2) where the cryocooler is set. The EOM2, used for the phase modulation which is required to lock the frequency laser to the cavity resonance via the Pound-Drever-Hall technique (PDH), is placed just before the second Michelson interferometer. Its long arm is closed by the reflexion on the entrance mirror of the cavity and the corresponding interference, detected on PD2, allows the monitoring and the cancellation of Doppler shifts. A photodiode (PD3) is used to detect residual amplitude modulations (RAM) of the EOM2 [6] and a second one (PD4) for the detection of the PDH error signal.

One of the challenges is the control of the phase of the laser along the beam path. Such phase noise comes from optical fibers, Doopler effect (due to residual motion of the cavity), fluctuations of refractive index and temperature variations of the optical supports. To compensate these phase noises, two Michelson interferometers are implemented, in which a long arm is phase locked to a short reference arm [5]. A difficulty is the realization of a reference arm with length noise below -194 dB m^2/Hz (slope in f^{-3}) in the Fourier frequencies of interest (0.01 Hz - 1 kHz) that is compatible with the thermal noise of the cavity.

VI. CONCLUSION

We are developing a laser stabilized to an ultra-stable cavity in silicon at 17 K. The last results of this work will be presented at the conference, specifically the noise of the reference arm used in the Michelson interferometers. We will also show the influence of the cryocooler on the cavity, including the effect of temperature fluctuations, vibration level and its induced residual motion to the cavity.

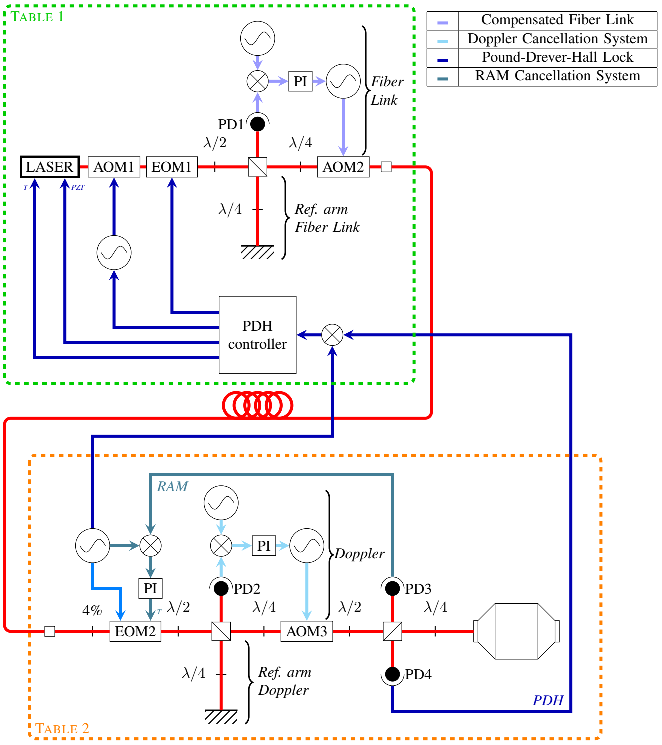

Fig. 2. Principle of the optical setup. AOM: acousto-optic modulator, EOM: electro-optic modulator, PD: photodiode, PI: proportional integrator controller

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