Investigation of a high-finesse silicon optical resonator at cryogenic temperatures

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Optical cavities with low sensitivity to temperature and mechanical forces are of significant importance for precision measurements in the optical and microwave frequency domain. Cryogenic operation of a cavity reduces the limitations of frequency stability caused by Brownian fluctuations. Another outstanding feature of crystalline cryogenic optical resonators is the absence of length drift.

Silicon, a machinable optical material, is available with high purity and large size. It possesses two zero crossings of the CTE, at 17 K and 126 K, and an ultralow CTE below 4 K, high stiffness and low mechanical dissipation. Recently, ultra-high frequency stability and an extremely low long-term drift of a silicon resonator operated at 126 K has been demonstrated[1].

In our experiment we report on the first demonstration and characterization of ultra-stable silicon resonator at temperatures down to 1.5 K. The resonator is 25 cm long and exhibits a high finesse (> 200 000). The calculated Brownian noise instability limit is 5×10^{-18}. The resonator is mounted inside a pulse-tube cooler cryostat equipped with a Joule-Thomson stage. A 1.5 µm fiber laser is frequency-stabilized to the resonator using the Pound-Drever-Hall technique. The laser frequency is measured with a femto-second frequency comb that is phase-locked to an ultra-stable 1064 nm laser with a 10^{-15}short-term frequency instability. The reference of the comb is a pair of active hydrogen masers. A preliminary measurement of the medium-term instability of the Si resonator showed that it is less than 1×10^{-14} at several 1000 s). No discernible long-term drift was observed so far.

The CTE of the cavity in its support structure was precisely measured in the temperature range between 1.5 K and 20 K. At 1.5 K, the CTE was measured to be 2×10^{-12} K, the lowest CTE value measured so far. The temperature of the zero CTE crossing was determined to occur at 16.8 K with the a CTE temperature derivative approximately a factor 20 smaller than for a resonator operated at the second zero-CTE temperature 124.2 K (Ref.1). We have also measured the resonator sensitivity to laser power variation, and the temperature stability. With the appropriate stabilization systems for these two parameters, already implemented, we foresee the potential to reach frequency instability at the few 10^{-17} level. Work is in progress to measure the residual long-term drift of the Si resonator and the short-term frequency instability by comparison with a second Si resonator.

[1] T. Kessler, C. Hagemann, C. Grebing, T. Legero, U.Sterr, and F. Riehle, Nature Photonics 6, 687, (2012)