A Close-Cycle Cooled Ultra-Stable Optical Cavity at 124 K

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The PTB cryogenic crystalline silicon optical cavities are the most frequency stable optical oscillators reaching 3.0×10^{-17} fractional frequency stability[1,2]. The reduction of thermal noise obtained using crystalline silicon with low mechanical losses for the cavity spacer and mirror substrates, and cooling to the zero crossing of the coefficient of thermal expansion of silicon at about 124 K, is fundamental to the realization of their frequency stability, as is the suppression of all technical noise sources. Therefore, a low vibration cooling system is instrumental to achieve the performance demonstrated by these ultra-stable optical resonators.

The PTB silicon cavities are cooled circulating cold nitrogen gas evaporated from a liquid nitrogen dewar[3]. Temperature stabilization is achieved controlling the cold gas flow by adjusting the liquid nitrogen evaporation rate by varying the current passing through a resistive heater installed in the dewar. This cooling system does not have any moving part and is intrinsically low vibration. However, each cavity setup consumes roughly 400 liters of liquid nitrogen per week, requiring refilling the liquid nitrogen dewar every two to three days. Liquid nitrogen refills perturb the cold nitrogen flow through the heat exchanger resulting in sub-mK-level temperature fluctuations affecting the long-term frequency stability of the resonators.

To obviate these issues, we replaced the liquid-nitrogen-based cooling system for one of the silicon cavities with a system where the cooling power is provided by a single-stage pulse-tube cryo-cooler. The cryo-cooler is installed in a separate vacuum chamber and the cavity is cooled by a flow of cold helium gas circulating between a heat exchanger connected to the pulse-tube cold finger and a heat exchanger connected to the outermost radiation shield surrounding the optical cavity. Vacuum-isolated flexible hoses are used to isolate the cavity from vibrations of the pulse-tube cooler. Temperature stabilization is achieved controlling the rotation speed of the cryogenic fan used to maintain helium flow. The cavity can be kept at 124 K operating the cryo-cooler with a cooling power of roughly 35 W at 85 K. The system demonstrates sub-mK temperature stability at the outer shield.

We will present the cooling system design and characterization, including measurements of the temperature stability, acceleration noise, and frequency stability of the ultra-stable cavity system.

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