Ultrastable, 10 mHz linewidth lasers based on cryogenic silicon resonators

T. Legero[1], D.G. Matei[1], S. Häfner[1], C. Grebing[1], R. Weyrich[1], F. Riehle[1], and U. Sterr[1]
W. Zhang[2], J. Robinson[2], L. Sonderhouse[2], and J. Ye[2]
[1]Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
[2]JILA, National Institute of Standards and Technology and University of Colorado,
440 UCB, Boulder, CO 80309-0440, USA
E-mail: Thomas.Legero@ptb.de

Laser can emit polarized light with high intensity and superior spatial and temporal coherence. The corresponding spectral purity and high frequency stability revolutionized optical spectroscopy and allowed for the study and control of internal states of atoms and molecules. Today's most stable and spectrally narrow laser sources are essential for probing ultra narrow optical clock transitions [1,2], precision tests of relativity [3] and the detection of gravitational waves [4].

The most common concept for ultrahigh frequency stability and narrow linewidth relies on stabilization of a laser system to a passive Fabry-Pérot resonator [5] with the Pound-Drever-Hall (PDH) stabilization technique [6]. The fractional frequency stability of the laser is then identical to the fractional optical-length stability of the resonator. This sets the highest requirements on the isolation of the resonator from temperature and pressure fluctuations, as well as from seismic and acoustic vibrations. In addition to technical noise, inevitable Brownian thermal noise fundamentally limits the resonators length stability [7]. During the last years there has been a remarkable progress in reducing the resonators thermal noise limit [8-10].

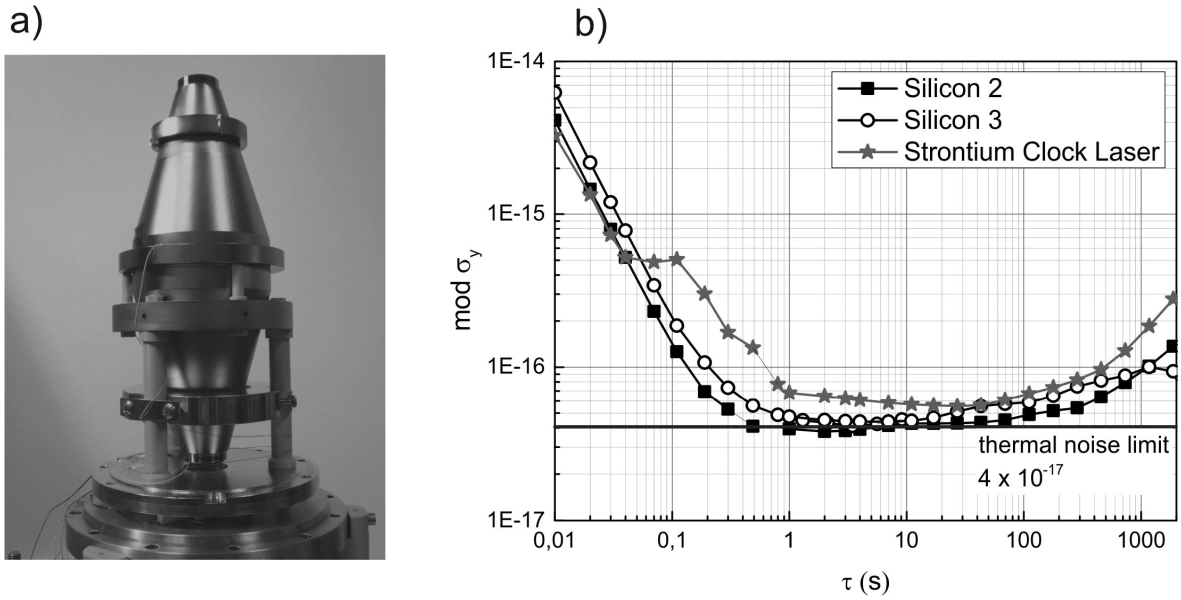

Fig. 6 Photograph of one of the silicon resonators resting on a stiff tripod support (a). Individual frequency instability determined from a three-cornered hat comparison of the two silicon based laser systems (Silicon 2 and 3) working at 1.5 μm [8] and a 698 nm laser stabilized on a 48 cm long ULE resonator [9].

We follow this approach by stabilizing a commercial DFB fiber laser to a Fabry-Pérot resonator made of single-crystal silicon cooled to 124 K [11]. Both the cavity spacer and the mirror substrates are made out of the same crystal. The low temperature and the high mechanical Q-factor of silicon result in an exceptional low level of thermal noise. Setting up two independent laser systems employing individual silicon resonators we demonstrate an unprecedented fractional frequency instability of 4×10^{-17}. The linewidth of the emitted light at 1.5 µm is 10 mHz, corresponding to a coherence time of 100s.

Each resonator employs a 212 mm long conical shaped silicon spacer optically contacted to silicon mirrors with high-reflectivity Ta_2O_5/SiO_2-coatings (Fig 1 a). Both resonators show a finesse close to 500 000. The resonators' thermal noise is dominated by the contribution of the mirror coatings. The expected fractional frequency instability is calculated to be 4×10^{-17}. Each resonator is placed in a vacuum chamber with residual pressure of 10^{-9} mbar. They are actively cooled to the cross-over temperature of silicon's coefficient of thermal expansion at around 124 K. Additional thermal shielding further suppresses the impact of residual temperature fluctuations. All other technical noise sources, such as seismic and acoustic vibrations as well as residual amplitude modulation [12], have been carefully studied and suppressed to levels well below the expected thermal noise limit.

We confirmed the individual frequency stabilities of the two silicon laser systems by a three-cornered hat comparison [13] with a third ultra-stable laser at 698 nm [14]. This additional laser serves as interrogation laser in PTB's strontium-lattice clock. Stabilized on a 48 cm long resonator, made from ultra low expansion glass, this laser shows a thermal noise limited frequency instability of mod $\sigma_y \approx 7\times10^{-17}$. A femtosecond frequency comb is used to bridge the wavelength gap between the 1.5 µm systems and the 698 nm laser [10]. The necessary optical fiber links between the lasers and the frequency comb are stabilized by active fiber noise cancelation [15]. The modified Allan deviations of both silicon-based laser systems show a thermal-noise-limited flicker floor at mod $\sigma_y = 4\times10^{-17}$ for averaging times between 1s and 100s.

The direct beat signal between the two 1.5 µm laser systems was recorded over periods of 200 s and spectrally analyzed by Fast-Fourier-Transform. On average the width of the beat signal is as narrow as 13 mHz, indicating an individual linewidth of the lasers at around 10 mHz.

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