Ultrastable Lasers – New Developments and Challenges

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Lasers with long coherence time and narrow linewidth are an essential tool for quantum sensors and clocks. State-of-the-art optical oscillators employing cryogenic reference cavities with highly reflective dielectric coatings reach now instabilities of 4×10^{-17} for averaging times from seconds to hundreds of seconds [1,2]. This performance is limited by the Brownian thermal noise associated with the mechanical dissipation of the dielectric Ta_2O_5/SiO_2 mirror coatings.

Recently, crystalline AlGaAs/GaAs Bragg reflectors have emerged as a promising candidate for reducing coating thermal noise due to their low mechanical loss [3,4]. We present measurements of the frequency noise of fully crystalline cryogenic reference cavities with $Al_{0.92}Ga_{0.08}As/GaAs$ optical coatings applied to silicon substrates which are contacted to silicon spacers at 4 K, 16 K and 124 K. We have confirmed the reduced Brownian noise as expected from the low mechanical loss, however novel noise sources were identified that have so far prevented the expected improvements [5,6]. One contribution appears as fluctuations of the coating's intrinsic birefringence, while the other one appears as fluctuations with large-scale spatial correlations after averaging away the birefringent noise. To gain more insight into the physical mechanisms that may be related to the semiconductor properties of AlGaAs/GaAs, we are now investigating the non-thermal response of the coatings to changes in intracavity power, and to broadband illumination over a broader temperature range.

We will also report on alternatives for improving the stability, like nanostructured materials [7] or increased mode sizes. Finally, we will give an outlook for more reliable, maintenance free and robust cryogenic silicon cavity setups that will enable also transportable optical clocks to benefit from their performance.

References

[1] J. M. Robinson, E. Oelker, W. R. Milner, W. Zhang, T. Legero, D. G. Matei, F. Riehle, U. Sterr and J. Ye, "Crystalline optical cavity at 4 K with thermal noise limited instability and ultralow drift," Optica, 6, 240, 2019.

[2] D. G. Matei, T. Legero, S. Häfner, C. Grebing, R. Weyrich, W. Zhang, L. Sonderhouse, J. M. Robinson, J. Ye, F. Riehle and U. Sterr, "1.5 µm lasers with sub-10 mHz linewidth," Phys. Rev. Lett., 118, 263202, 2017.

[3] G. D. Cole, W. Zhang, M. J. Martin, J. Ye and M. Aspelmeyer, "Tenfold reduction of Brownian noise in optical interferometry," Nature Photonics, 7, 644, 2013.

[4] G. D. Cole, S. Ballmer, G. Billingsley, S. B. Cataño-Lopez, M. Fejer, P. Fritschel, A. M. Gretarsson, G. M. Harry, D. Kedar, T. Legero, C. Makarem, S. D. Penn, D. Reitze, J. Steinlechner, U. Sterr, S. Tanioka, G. W. Truong, J. Ye and J. Yu, "Substrate-transferred GaAs/AlGaAs crystalline coatings for gravitational-wave detectors," Appl. Phys. Lett., 122, 110502, 2023.

[5] D. Kedar, J. Yu, E. Oelker, A. Staron, W. R. Milner, J. M. Robinson, T. Legero, F. Riehle, U. Sterr and J. Ye, "Frequency stability of cryogenic silicon cavities with semiconductor crystalline coatings," Optica, 10, 464, 2023.

[6] J. Yu, D. Kedar, S. Häfner, T. Legero, F. Riehle, S. Herbers, D. Nicolodi, C. Y. Ma, J. M. Robinson, E. Oelker, J. Ye and U. Sterr, "Excess noise in highly reflective crystalline mirror coatings," arXiv:2210.15671 [physics.optics], 2022.

[7] J. Dickmann, S. Sauer, J. Meyer, M. Gaedtke, T. Siefke, U. Brückner, J. Plentz and S. Kroker, "Experimental realization of a 12,000-finesse laser cavity based on a low-noise microstructured mirror," Commun. Phys., 6, 16, 2023.