Lower Laser Noise with Multi-Higher Order Mode Locking to Reduced Brownian Thermal Noise

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Ultra-stable lasers are important for high-resolution spectroscopy and optical atomic clocks [1]. Laser frequency noise limits precision in measurement and bounds frequency standards. It affects not only the resolvability and interaction times with optical-atomic transitions but also degrades clock stability through the optical 'Dick effect' [2]. To achieve high stability a laser is typically locked with feedback control to an optical cavity resonator using the Pound-Drever-Hall technique [3]. The inherent length stability of an optical cavity is imparted upon a laser's frequency. Optical cavities are bounded in their ultimate stability by the random $1/\sqrt{f}$ thermal motion in their reflective coatings. Reducing or mitigating this fundamental thermodynamic bound is an important area of research for the science of precision measurement and optical time standards.

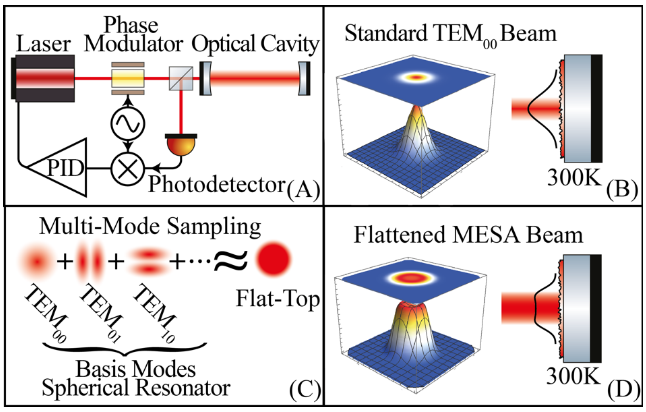

Fig.1. Figure 1:(A) Classic Pound-Drever-Hall locking typically implements a (B) TEM00 Gaussian Beam that is strongly weighted to the center reducing the averaging potential of beams incident on mirrors. By combining the basis set of Hermite Gaussian Modes (C) a Flat-top beam can be synthesized similar to the diffraction limited 'MESA' beam (D) that maximizes the spread of laser light on mirrors while steeply cutting off at the edges to avoid clipping.

We will outline a new approach to mitigating fundamental Brownian coating thermal noise in optical cavities using multiple higher order TEM gaussian modes [4]. By blending the readout signals of multiple higher order modes, the effective sampling area of mirrors increases. This improves the averaging of thermal motion, thereby lowering the overall length noise. We propose a scheme where a top-hat like beam is effectively synthesized from a weighted combination of signals fed back to a laser. We will present results of a theoretical study into this new scheme and progress and plans for an experimental implementation.

We will show that an experimentally feasible implementation of a three-mode lock – combining modes TEM_{00}, TEM_{02}, and TEM_{20} – can reduce overall coating thermal noise by a factor of 1.6, equivalent to cooling the mirrors to 120 K. Such improvements are multiplicative with advancements in materials, cryogenics, and cavity lengthening approaches.

We will also outline the achievable bounds on thermal noise improvements for many higher order modes (more than three) and prospects for implementation in in the laboratory.

References

[1] A. D. Ludlow, X. Huang, M. Notcutt, T. Zanon-Willette, S. M. Foreman, M. M. Boyd, S. Blatt, and J. Ye, *Compact, Thermal-Noise-Limited Optical Cavity for Diode Laser Stabilization at 1×10^{-15}*, Opt. Lett., OL **32**, 641 (2007).

[2] A. Quessada, R. P. Kovacich, I. ne Courtillot, A. Clairon, G. Santarelli, and P. Lemonde, *The Dick Effect for an Optical Frequency Standard*, J. Opt. B: Quantum Semiclass. Opt. **5**, S150 (2003).

[3] R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, *Laser Phase and Frequency Stabilization Using an Optical Resonator*, Appl. Phys. B **31**, 97 (1983).

[4] A. Wade and K. McKenzie, *Mirror Coating-Thermal-Noise Mitigation Using Multi-Spatial-Mode Cavity Readout*, Phys. Rev. A **106**, 023511 (2022).