Design and development of an ultra-stable high finesse cavity for all-optical portable atomic clock applications

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Portable optical atomic clocks are indispensable tools for PNT (positioning, navigation, and timing) applications in the civil and strategic sectors. Such clocks may form the backbone of a more resilient PNT system and allow a host of other applications such as better network communication, synchronization of power grids[1,2] etc. These clocks use a dipole forbidden (narrow linewidth, $\Delta\nu$) optical transition as a "clock" transition (center frequency ν) and thus have better stability compared to their microwave counterparts due to a higher quality factor ($Q = \nu/\Delta\nu$) arising from the optical transition[1].

To coherently probe a dipole-forbidden optical clock transition, a prerequisite is an ultra-stable narrow linewidth (Hz or sub-Hz) laser (clock laser), which serves as a local oscillator. Using the PDH (Pound-Drever-Hall) technique of laser frequency stabilization, the fractional stability in length ($\Delta L/L$) of an ultra-stable Fabry-Perot (FP) cavity with length L is transferred to the clock laser (oscillator with frequency ν) according to equation $\frac{\Delta L}{L} = -\frac{\Delta\nu}{\nu}$. This lowers the frequency instability ($\Delta\nu/\nu$) of the clock laser relative to the fluctuations in the cavity length[3].

The stability in the length of a FP cavity is limited by fundamental thermal noise and is adversely affected by external perturbations such as deformation due to self-weight, fluctuation in temperature, vibrational noise, acoustic noise[3], etc. Addressing these potential noise sources while developing an ultra-stable high finesse cavity for a trapped ion-based portable atomic clock presents a formidable task.

In my talk, I will showcase the application of finite element analysis techniques (using ANSYS package) to identify the Airy points for a cavity spacer constructed from ultra-low expansion (ULE) glass and mirror substrates made of fused silica (FS) for a trapped ion-based portable atomic clock. Due to low acceleration forces (such as self-weight due to gravity), stability in cavity length can suffer due to Poisson's effect and mirror tilt. Deformation in length due to self-weight can be minimized by mounting the cavity on its Airy points, which also ensures less mirror tilt[4]. Additionally, we elucidate how the fundamental thermal noise floor is influenced by the cavity length and radius of curvature (ROC) of mirrors, thereby offering insights into the optimization of cavity length and choice of mirror ROC.

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