Dynamics and Stability of an Optically Levitated Mirror

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Abstract: We characterise the dynamics of a vertical Fabry-Pérot cavity, where the upper mirror levitates due to radiation pressure force. The system is found naturally unstable, and we study two-laser trapping/damping schemes and photothermal effects. © 2020 The Authors

Optomechanics explores the interaction between electromagnetic radiation pressure force and mechanical motion. The canonical example is a Fabry-Pérot cavity, one end of which oscillates on a spring. This interaction between different physical systems opens up many applications. We can perform precision metrology by coupling the mechanical motion to some force of interest and reading out its position via the cavity field [2], and thermal motion of the oscillator can be cooled using optical techniques [3]. A quantum state of light in the cavity could generate a macroscopic quantum superposition in the mechanical oscillator [4], providing a platform for tests of quantum decoherence [6] and models of semiclassical quantum gravity [7].

The main source of noise and decoherence in optomechanical systems is generally thermal effects from the environment, which will couple into the system via the mechanical oscillator and can be significant even at cryogenic temperatures. There are several proposals to replace the mechanical spring with optical trapping and levitation [8-10], which can also lead to optical springs with much higher Q factors than what is often is possible mechanically [11] due to the lack of internal mechanical strains in the oscillation. This approach achieves decoupling from the environment, without the drawback of scattering losses present in setups such as optical tweezers. These systems are also very flexible, as the properties of the ‘optical spring’ may be chosen by varying the power and frequency of the input laser.

We perform the first detailed characterisation of the resulting levitated optical spring, using an analytical perturbative approach. We use this to extract general features of the system dynamics and show that the behaviour is governed by a few dimensionless parameters. We study a one-dimensional system (Figure 1 a), for practical application stability may be achieved via a tripod [9] (Figure 1 b) or sandwich [10] configuration, or directly via magnetic confinement. Our analysis applies to all such configuration.

The difference in speed between the evolution of the light field and mechanical motion of the mirror allow us to analytically solve the equations of motion using a perturbative approach. We show that the mirror moves in an effective potential, in which it exhibits growing oscillations until falling out of the trapping region (Figure 2 a).
The dynamics can also be visualised in three-dimensional phase space, where the separation in timescales makes the dynamics effectively two-dimensional (Figure 2 b). This theory allows us to intuitively understand the global behaviour of the levitated optical cavity systems, characterising the trap width, oscillation frequencies, and heating rate in terms of a few dimensionless parameters.

**Figure 2** a) Motion of the mirror in the optical potential b) Trajectory in phase space c) Frequencies of oscillation in the central well, characterized by amplitude and a single dimensionless parameter ɣ.

We then use this theory to study two schemes of experimental interest. The first is two-laser trapping/damping, where a second detuned laser is used to stabilise the system. This is a common technique in optomechanics and was mentioned as a possibility for levitated systems in [9]. We perform a numerical search and identify all parameter regimes where stable trapping can occur. We find however that this is likely to be unsatisfactory, as for all such regimes the potential is very shallow and flat around the trapping region, and so experimental implementations may be better off pursuing other approaches such as feedback cooling. We next consider the effects of photothermal expansion of the mirror substrate due to heating by the intra-cavity laser. We find that in most cases, where this acts to shorten the effective optical path-length, this acts to further de-stabilise the system, and calculate the rate at which this happens. We show however that if the substrate can be engineered such that optical path-length is decreased by photothermal effects, then there will have a stabilising effect, which can overcome the natural instability of the system.

These results are available at [arXiv:1912.07789](https://arxiv.org/abs/1912.07789) [1]

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