Alignment requirements of Fabry-Perot microresonators for ion trap quantum information processing

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In recent years there has been rapid progress into realising a working universal quantum computer, in particular with the development of chip-based radio frequency (RF) ion traps. The next significant leap will come with successfully integrating optical cavities into these ion traps to allow for interaction between remote ions via photons as required for more efficient and scalable quantum networking schemes. Fibre-tip cavities are especially interesting for such applications as they enable highly efficient coupling of photons from the cavity into optical fibres for onward transmission [1]. Ideally, one would like to operate such micro-resonators in the near-concentric regime that provides the smallest cavity mode waist and thus strongest coupling to a trapped ion. However, the cavity mode becomes unstable in this limit, and in practice ion-cavity systems are often operated far away from this regime.

Here we analyse theoretically and numerically the effects of parallel off-axial misalignment in millimetre scale optical Fabry-Perot cavities to calculate the optimal parameters for atom-light coupling with fabrication tolerances. First, simple raytracing allows us to visualise the effect of misaligned cavities and calculate how the cavity mode is rotated off-axis as a function of the radius of curvature of both mirrors, the length of the cavity, and the parallel off-axial and mirror plane misalignment. In a second step, Gaussian beam optics is used to calculate the clipping losses induced by the tilted cavity mode missing the cavity mirrors. Numerical simulations of the resulting overlap integrals are compared with an approximate analytical solution which allows much faster evaluation and therefore is used for in-depth analysis of such a system.

Our model therefore quantifies the trade-off between small cavity waist and the resulting sensitivity to cavity alignment. For example, for typical experimental parameters [1,2] (mirror radius of curvature 0.7 mm, mirror diameter 0.140 mm, operation wavelength 850 nm) we calculate the misalignment that reduces the cavity lifetime by 1/e, i.e. to 37% of the perfectly aligned cavity. We find a maximum misalignment tolerance of 0.95 nm for a beam waist of 2.91 µm (cavity length of 1.397 mm), which increases to 11.0 nm for a waist of 4.33 µm (length of 1.386 mm), and 3.12 µm for a waist of 7.38 µm (length of 1.273 mm). In the parameter regimes of interest we derive a simple relation between cavity length, mirror radius, and misalignment sensitivity. Finally, we also consider the effect of mode matching of the misaligned cavity mode with the optical mode of the fibre for efficient cavity to fibre coupling.

In conclusion, we find that whilst near concentric regimes allow for strong atom-light coupling they are extremely sensitive to parallel off-axial misalignment. Our model allows us to calculate the minimum cavity mode waist for given manufacturing/alignment accuracies, as required to optimise photon-ion coupling for quantum information processing.

[1] G. Kaur Gulati et al., Sci. Rep. 7, 5556 (2017)

[2] H. Takahashi et al., Opt. Expr. 22, 31317 (2014)

Summary :

In recent years there has been rapid progress into realising a working universal quantum computer, in particular with the development of chip-based radio frequency ion traps. The next significant leap will come with successfully integrating optical cavities into these ion traps to allow for interaction between remote ions via photons as required for more efficient and scalable quantum networking schemes. Fibre-tip cavities are especially interesting for such applications as they enable highly efficient coupling of photons from the cavity into optical fibres for onward transmission.

Here we analyse theoretically and numerically the effects of parallel off-axial misalignment in millimetre scale optical Fabry-Perot cavities. While near-concentric cavity configurations produce the smallest mode waist and thus strongest coupling to a trapped ion, their mode is extremely sensitive to misalignment. Shorter cavities exhibit more robust modes, but at the cost of larger mode waists. For example, for typical experimental parameters (mirror radius of curvature 0.7 mm, mirror diameter 0.140 mm, operation wavelength 850 nm) we find that the cavity lifetime is reduced by a factor 1/e for a misalignment of 0.95 nm for a beam waist of 2.91 µm (cavity length of 1.397 mm), which increases to 11.0 nm for a waist of 4.33 µm (length of 1.386 mm), and 3.12 µm for a waist of 7.38 µm (length of 1.273 mm). In the parameter regimes of interest, we derive a simple relation between cavity length, mirror radius, and misalignment sensitivity. Finally, we also consider the effect of mode matching of the misaligned cavity mode with the optical mode of the fibre for efficient cavity to fibre coupling.

In conclusion, our model allows us to optimise photon-ion coupling in fibre-tip resonators for quantum information processing in the presence of finite fabrication and alignment tolerances.

L = 1.397mm, Beam waist = 2.9077um beam

10Mhz= 3.001nm miss

1 Mhz = 0.949251nm

L = 1.386mm ,Beam waist= 4.33um

10Mhz = 34.64nm

1Mhz = 10.97 um

L = 1.2725mm, Beam waist= 7.38um

10Mhz = 4394.88nm

1Mhz = 3115.97nm