Mode Shaping for Improved Optical Microcavity Performance

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Abstract: We develop a method that optimises cavity modes to increase the coupling between Fabry-Pérot optical cavities and quantum emitters. We find orders-of-magnitude cooperativity improvements when coupling to multiple emitters or using plano-concave geometries.

Fabry-Pérot optical cavities often provide the strong interface between single photons and quantum emitters that is crucial for quantum technology protocols, including single photon generation and remote entanglement. The traditionally spherical cavity mirrors lead to Gaussian beam cavity modes, but alternative mirrors shapes could realise non-Gaussian modes with advantageous properties. We develop a method that optimises the cavity mode and finds the corresponding mirror shape. We thus demonstrate the potential for dramatically strengthened light-matter interfaces, particularly for cavities coupling to multiple emitters, or for plano-concave cavities.

Our 'retroreflective optimisation' method [1] is a two-step process (depicted Fig. 1a-b). First, we parametrise the prospective cavity eigenmode as a superposition of transverse Gaussian modes and optimise the mode weights for the chosen task. Second, we construct the cavity mirror surface to retroreflect this optimised target mode, thus making the target mode a cavity eigenmode, which is confirmed through mode mixing calculations [2]. Though we may optimise any metric, we choose the 'internal cooperativity' C_{int}, which determines success probability for many applications including single photon production [3]. In the simplest example of an emitter in the centre of a cavity, an ideal geometry for single photon production, small modifications to the surface profile (Fig. 1c) create an eigenmode that focusses tightly on the emitter but avoids high clipping losses by occupying the mirror surface more evenly than any Gaussian beam (Fig. 1d).

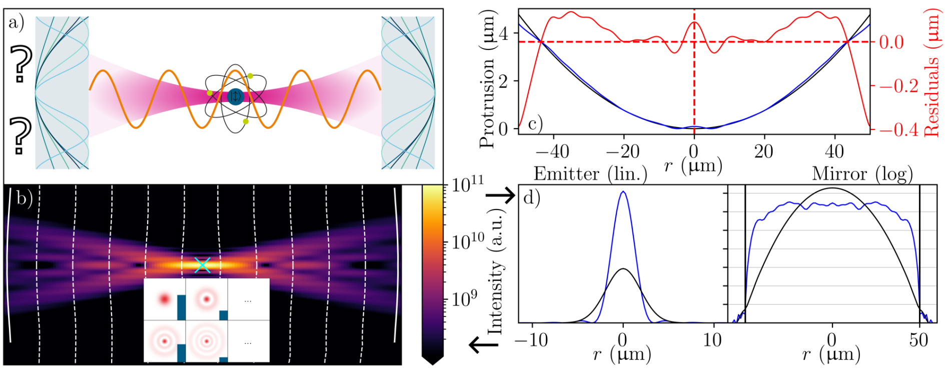

Fig. 1. a) Schematic of an emitter in the centre of an example standing-wave Fabry-Pérot cavity (length 500 μm, mirror diameter 70 μm, resonant wavelength 854 nm, and combined absoprtion and scattering losses 20 ppm). b) The cavity eigenmode is optimised in the Laguerre-Gauss basis (inset), with its equiphase surface (dashed lines) defining the mirror profile. The optimised mode (colour map) focusses tightly on the central emitter (cyan cross). c) Surface profile of (black) the best spherical mirror and (blue) the optimised surface with (red) residuals overlaid. d) Intensities of the (black) best Gaussian mode and (blue) eigenmode of the optimised cavity in the (left) emitter and (right) mirror transverse plane, with the vertical lines marking the mirror edges.

We first apply the retroreflective method to cavities with two emitters spaced equally on axis about the centre (Fig. 2), ideal for direct intra-cavity interaction or multiplexing. The best spherical mirror cavity generates a Gaussian mode that focusses between the emitters, but the optimised mode focusses strongly on both emitters (Fig. 2b). For our example, we find a 20-fold improvement in C_{int} (Fig. 2c), which could greatly improve intra-cavity gate speed and fidelity, or photon extraction probability, depending upon the application.

We also suggest mirror shaping for plano-concave cavities, which boast transverse misalignment insensitivity, and require only one non-planar mirror be fabricated. When using a spherical mirror, C_{int} is limited because the

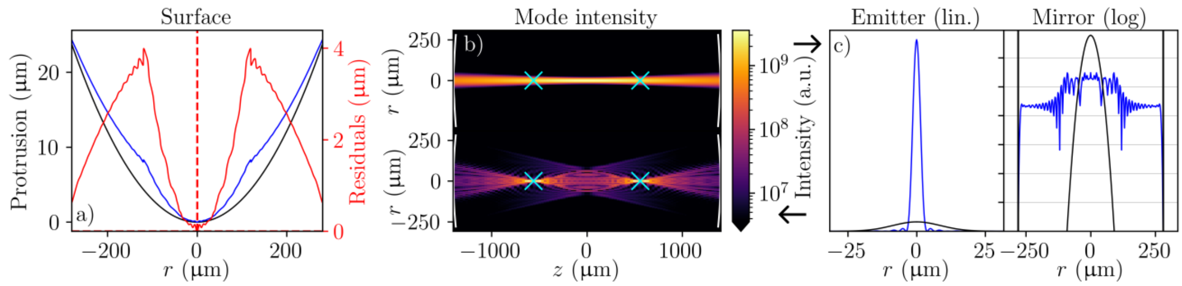

Fig. 2. Retroreflective optimisation for two emitters along the cavity axis (length 2.8 mm, mirror diameter 0.56 mm, emitter separation 1.12 mm, resonant wavelength 854 nm to target a Ca^+ transition, and combined scattering and absorption losses 20ppm). a) Surface profile of (black) the best spherical mirror and (blue) the optimised surface with (red) residuals overlaid. b) Cross section of the mode intensity for the (top) best Gaussian mode and (bottom) mode of the optimised cavity. Cyan crosses mark the emitter positions. c) Intensity of the (black) best Gaussian mode and (blue) eigenmode of the optimised cavity in the (left) emitter and (right) mirror transverse planes, with the vertical lines marking the mirror's edge.

Gaussian mode focusses on the planar mirror, not the central emitter. However, in an example (Fig. 3), retroreflective optimisation can increase C_{int} over an order of magnitude above the spherical mirror limit, with a few-parameter surface realising most of that improvement without the small-scale features (similar to Fig. 2a) that may be challenging to fabricate. For the largest mirror diameters, optimised plano-concave cavities even outperform any spherical-mirror concave-concave cavity that must tolerate significant misalignment, offering a combination of performance and misalignment tolerance unachievable without mirror shaping.

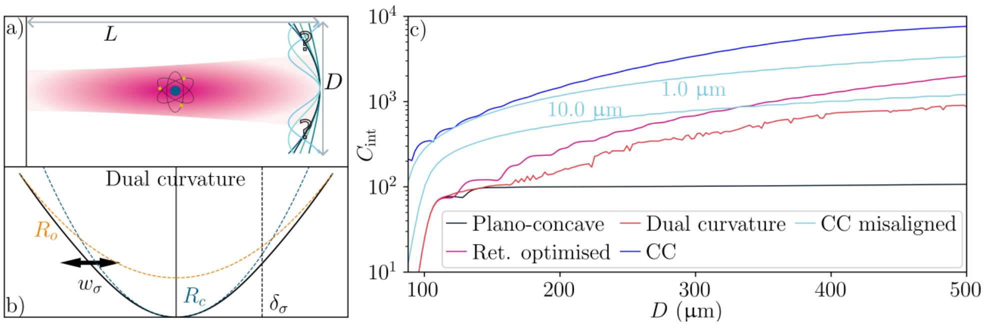

Fig. 3. a) The plano-concave geometry coupling a central emitter to a cavity of length L and non-planar mirror diameter D. b) Dual-curvature design with inner (R_c) and outer (R_o) radii of curvature, and transition region of width w_σ at radial coordinate δ_σ. c) Optimised C_{int} as a function of D for cavity length 1 mm, resonant wavelength 1033 nm to target an Sr^+ transition, and combined absorption and scattering losses 20ppm. The C_{int} is shown for plano-concave cavities with optimised-curvature spherical mirrors, retroreflective optimised mirrors, and the dual curvature mirrors, and concave-concave cavities (denoted 'CC') with (blue) no transverse mirror misalignment, or (light blue) misalignment labelled on the corresponding line.

We have developed a cavity optimisation method that reveals applications where mirror shaping can dramatically increase performance. These include cavities that couple to multiple emitters, with potential to quarter the infidelity of intra-cavity gate operations, while increasing speed up to 20-fold, in the example two-emitter case. There is similar scope for improvement, even with simple mirror profiles, in plano-concave designs, enabling transformative protocol success and speed improvements in a geometry that offers misalignment tolerance and easier integration into scalable technologies.

References

1. W. J. Hughes and P. Horak, "Retroreflective surface optimisation for optical cavities with custom mirror profiles," arXiv e-prints arXiv:2508.14712 (2025).
2. D. Kleckner, W. T. M. Irvine, S. S. R. Oemrawsingh, and D. Bouwmeester, "Diffraction-limited high-finesse optical cavities," Phys. Rev. A **81**, 043814 (2010).
3. H. Goto, S. Mizukami, Y. Tokunaga, and T. Aoki, "Figure of merit for single-photon generation based on cavity quantum electrodynamics," Phys. Rev. A **99**, 053843 (2019).