AN OPTICAL CAVITY WITH A STRONGLY FOCUSED MODE

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Motivation

Atom, photon interfaces are on of the building blocks of the future quantum information protocols. Accomplishing a strong interaction between the atom and the photons can be successfully done by high finesse and small volume cavities. However, this method requires sophisticated dielectric coatings and stabilization of the cavity against even small vibrations, which make it seem hard to scale up such atom-light interfaces to form quantum networks. An alternative method is to use a nearly concentric cavity , which has a ***strongly focused optical mode***[1].As a support of this argument, we have recently detected a substantial interaction between an atom and a focused light beam even without use of a cavity [3].

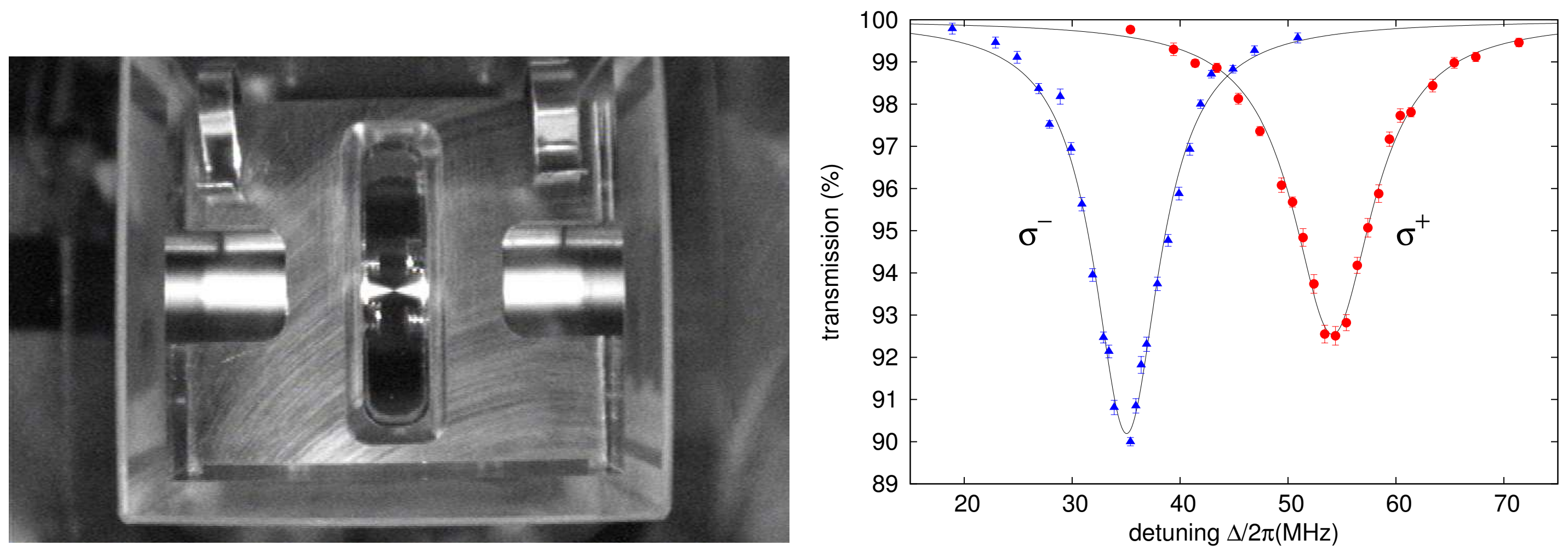


FIGURE 1: (Left) Our former set-up for single atom-light interface at the strong focusing regime for free space. (Right) Transmission of probe beam through single atom for different polarizations [4].

Simple estimations show that in such a cavity one can expect a large atom-light coupling constant g_0 such that g_0/h is much larger than the spontaneous decay rate of the atom, even for a relatively large mirror separation. Our aim is to achieve a strong coupling between a single atom and light by using a near concentric optical resonator..

Theory

We quantify the interaction of the incoming light with a single two-level atom via scattering ratio. The field amplitude at a location of the atom E_A is obtained by propagating the vectorial field $\vec{E}_\mathrm{F}$ after the lens to the focus with the help of Green theorem. Once we have an analytical expression for this field, the scattering ratio can be computed.

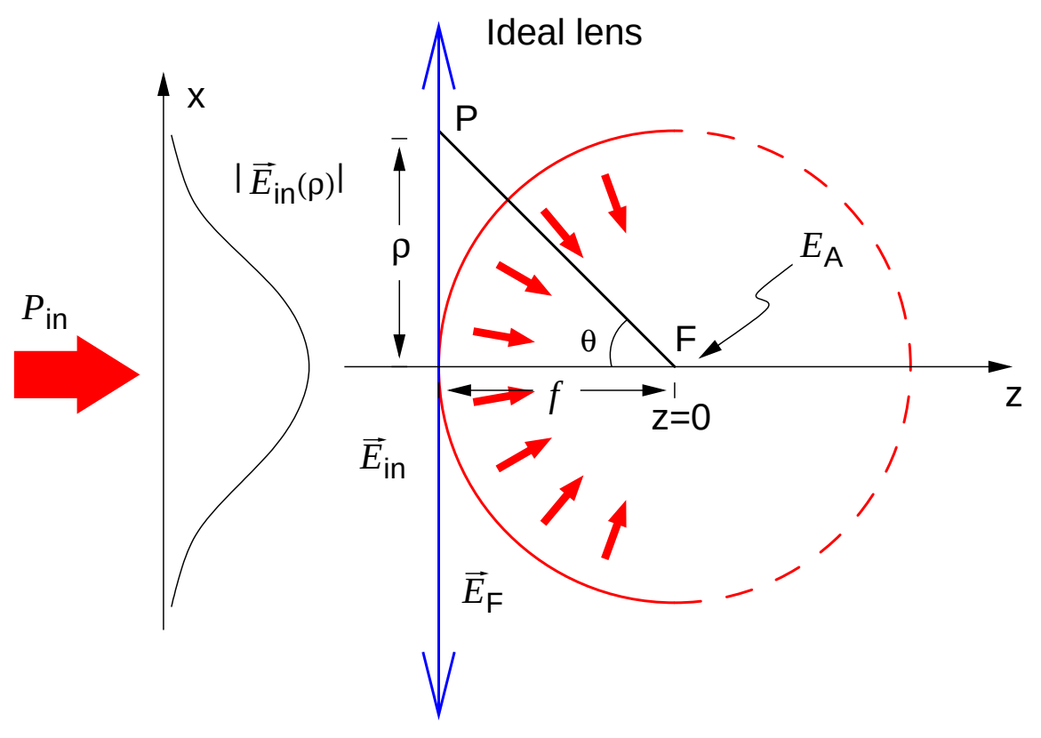
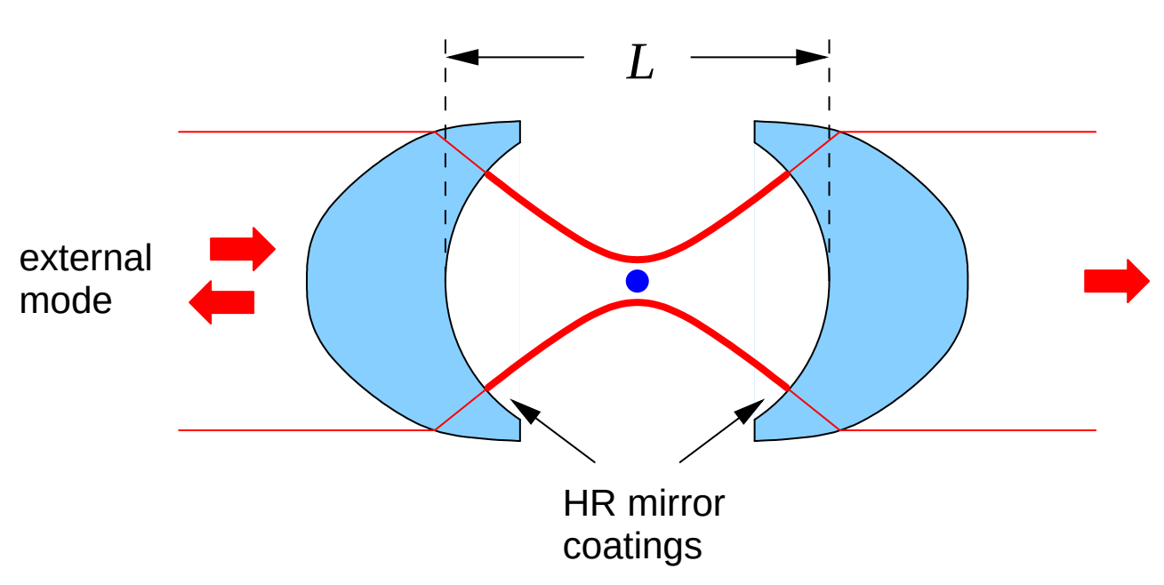


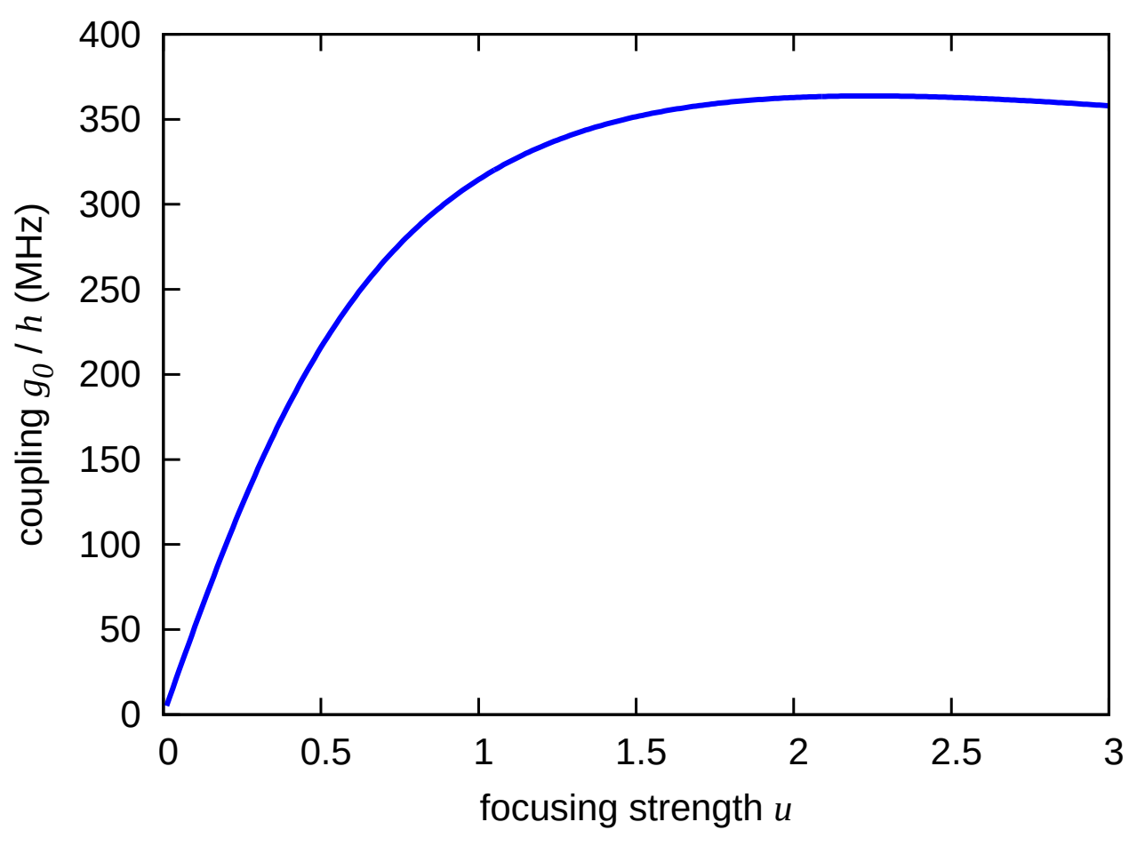
FIGURE 2: (Left) Wavefront of a spherical focusing field after an ideal lens with a focal length f. The incoming field $\vec{E}_\mathrm{in}$ assumed to have a Gaussian profile with minimal waist w_L. Subsequent calculations are done base on the focusing parameter $u = w_\mathrm{L}/f$.

$$R_\mathrm{sc} = \frac{P_\mathrm{sc}}{P_\mathrm{in}} = \frac{3}{4u^3}\mathrm{e}^{2/u^2}\left[\Gamma\left(\frac{1}{4},\frac{1}{u^2}\right) + u\Gamma\left(\frac{1}{4},\frac{1}{u^2}\right)\right]^2$$

Cavity QED with focused beams

One can substantially relax the mirror coating requirements that are needed for observation of strong coupling between atom and photon and compensate it by increasing the focusing strength. In a cavity with discrete mode spectrum, this strong focusing can result in a large atom-light coupling constant g_0 such that g_0/h is much larger than the spontaneous decay rate of the atom. We have performed a field quantization for a strongly focused Gaussian beams. We can express the g_0 dependence on focusing strength via the scattering ratio.





$$\mathrm{E_f} = \sqrt{\frac{2\pi\hbar\omega R_\mathrm{sc}}{3\lambda^2 L\epsilon_0}} \qquad \mathrm{g}_0 = \mathrm{E_f d_{eff}} = \hbar\sqrt{\frac{\pi c R_\mathrm{sc}}{\tau L}}$$

FIGURE 3: (Left) A nearly concentric optical cavity formed by a pair of meniscus lenses. The lens converts a Gaussian mode into the mode of the cavity. (Right) Coupling strength of the strongly focused mode determined using Jaynes-Cummings model on a closed transition on the D2 line of ^{87}Rb atom with lifetime $\tau = 26.3\,\mathrm{ns}$.

Diffraction at the edges of a near concentric resonator limits the achievable finesse [2].Under the assumption that the cavity eigenmode has a Gaussian angular profile, the power left within the cavity mirrors after one round-trip can be estimated as

$$\rho \approx R - \exp^{\frac{-2r^2}{\omega_z^2}}$$

where, R is the reflectivity of the cavity mirrors, r is the radius of the mirror from the optical axis and ω_z is the beam waist at the mirror.The finesse of the optical resonator can be expressed in terms of the power left after one round-trip as

$$\mathcal{F} = \frac{\pi}{2\arcsin(\frac{1-\sqrt{\rho}}{2\sqrt[4]{\rho}})}$$

Experiment

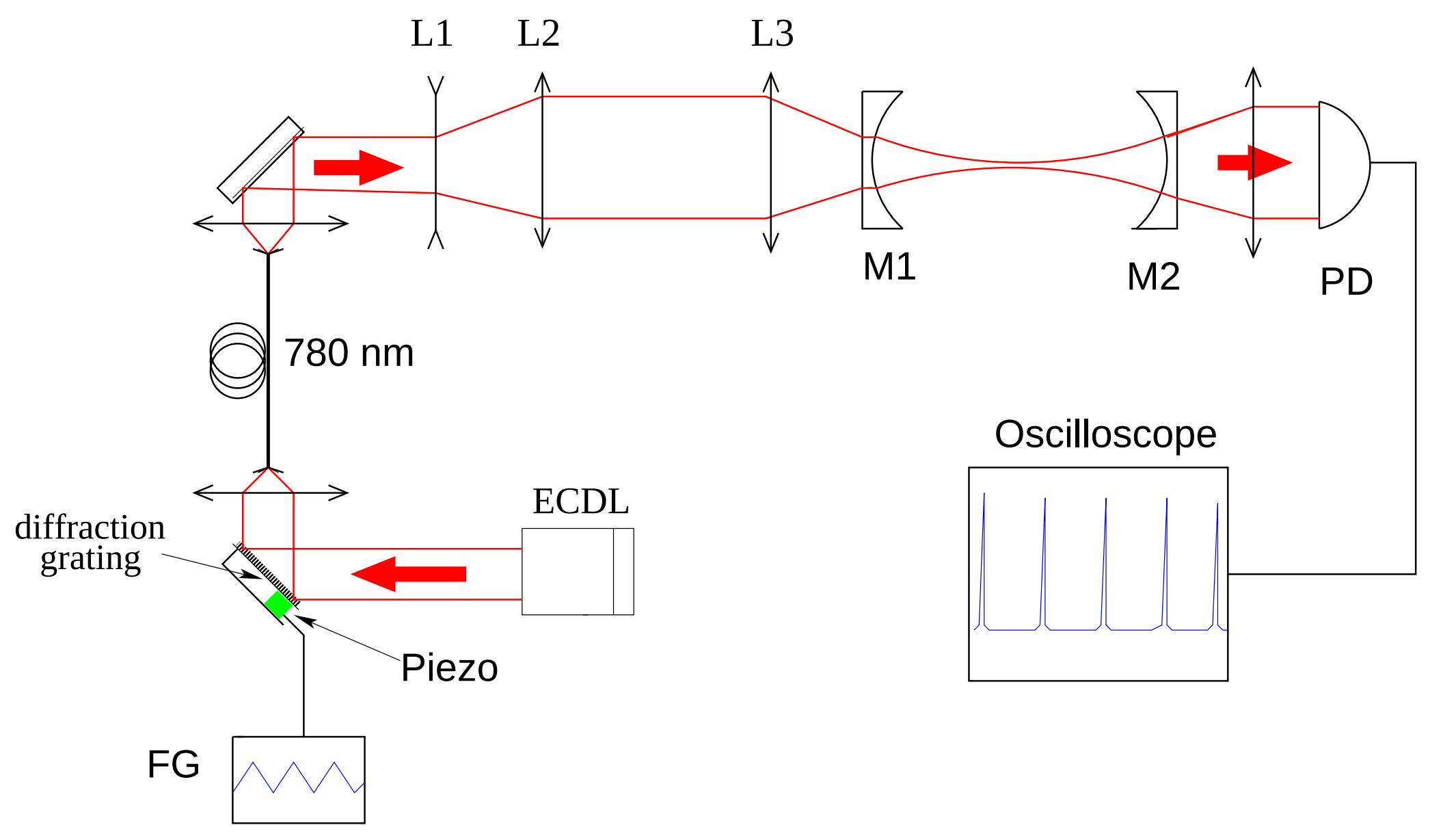


FIGURE 4: Th external cavity diode laser (ECDL) is scanned by changing the angle of the diffraction grating by sending saw-tooth voltage, which is created by the function generator (FG), to the piezo. The first lens (L1) and the second lens (L2) changes the beam waist and the third lens (L3) prepares the mode matching (i.e. the radius of curvature of the beam wavefront should be the same as the radius of curvature of the cavity mirrors).The transmitted light is picked up by the photodetector (PD) and sent to the oscilloscope.

Results

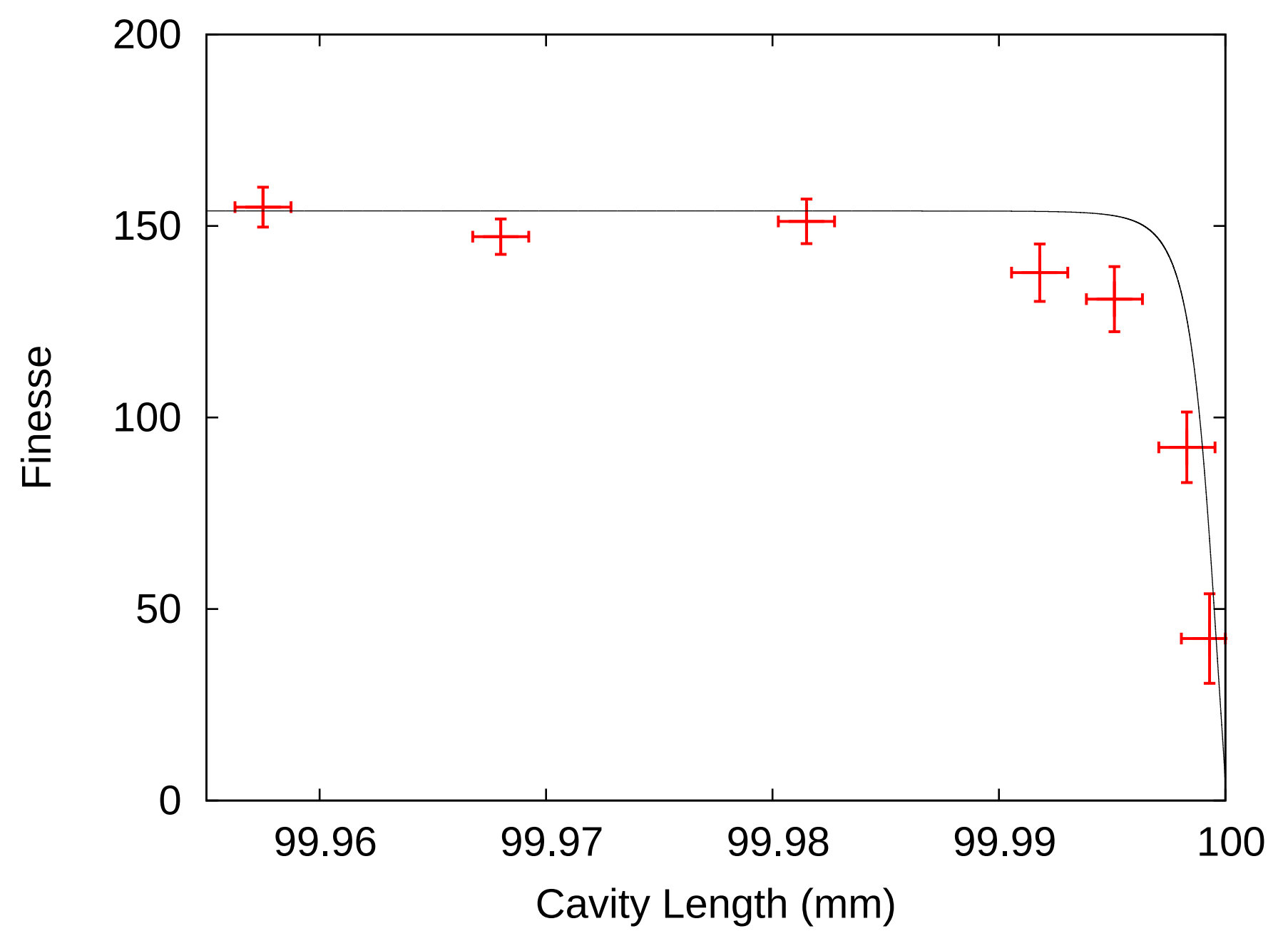


FIGURE 5: (Left)Cavity finesse dependence on the cavity length is measured. The radius of curvature of the mirrors is 50 mm and the reflectivity of the mirrors is 96%.The data is taken at room temperature and atmospheric pressure. The solid curve is calculated by considering the effect of the mirror reflectivity and diffraction loss on the cavity finesse, which is given in the $\mathcal{F}$ formula.

We have designed anaclastic lenses with a reflective coating in the spherical surface, where we expect to achieve higher focusing and slightly higher finesse (97% reflectivity).

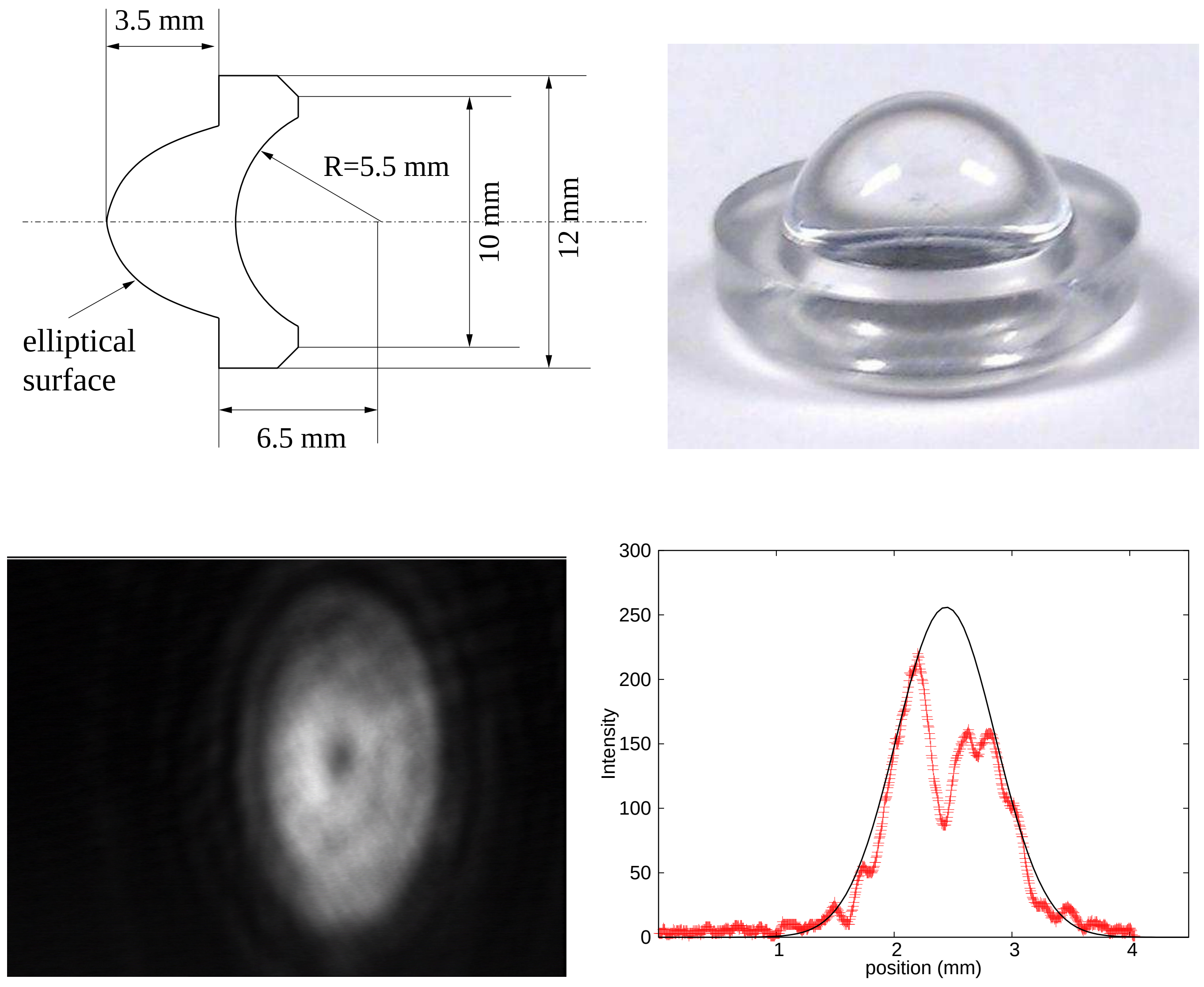


FIGURE 6: (Top Left) The cavity lens design. (Top Right) The cavity lens. the material is Zeonex 480R.(Bottom Left) A far-zone image of a spherical Gaussian beam that is reflected from the spherical surface of the cavity lens and collimated by a lens. The image is taken by a linear CCD. (Bottom Right) The beam profile of the reflected beam and the Gaussian beam profile comparison.

References

[1] S. E. Morin, et al., "Strong Atom-Cavity Coupling over Large Volumes and the Observation of Subnatural Intracavity Atomic Linewidths," *Phys. Rev. Lett*, **73**, pp 1489-1492, (1994)

[2] A. Haase, et al., "Detecting magnetically guided atoms with an optical cavity," *Optics Letters*, **31**, pp 268-270, (2006)

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[4] M. K.Tey, et al.,"Strong interaction of light with a single trapped atom without the need for a cavity," *Nature Physics*, **4**, pp 924-27, (2008).