

An objective lens for efficient fluorescence detection of single atoms

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Abstract: We present the design of a diffraction limited, long working distance monochromatic objective lens for efficient light collection. Consisting of four spherical lenses, it has a numerical aperture of 0.29, an effective focal length of 36 mm and a working distance of 36.5 mm. This inexpensive system allows us to detect $8 \cdot 10^4$ fluorescence photons per second from a single cesium atom stored in a magneto-optical trap.

Key words: Fluorescence detection – atom trapping

1. Introduction

The optical detection of individual trapped particles, such as single ions in a Paul trap [1] or neutral atoms in a magneto-optical trap [2], necessitate the development of efficient imaging optics. The ability to collect low levels of fluorescence light and the imaging of small objects require a high numerical aperture and diffraction limited performance, respectively. Additionally a long working distance is often necessary to provide access for laser beams or mechanical structures to the trap region.

Commercially available solutions for this application are either long working distance microscope objectives, which are relatively expensive, molded aspheric lenses with usually short focal lengths, or achromats, which have larger spot sizes. Special experimental geometries, such as imaging through the window of a vacuum cell, or specific geometrical restrictions, often require custom solutions.

2. Lens design

Our experimental requirement is the efficient collection of fluorescence light from single atoms in a magneto-optical trap (MOT) [3], see fig. 1. The trap is located inside a vacuum cell, which itself is situated

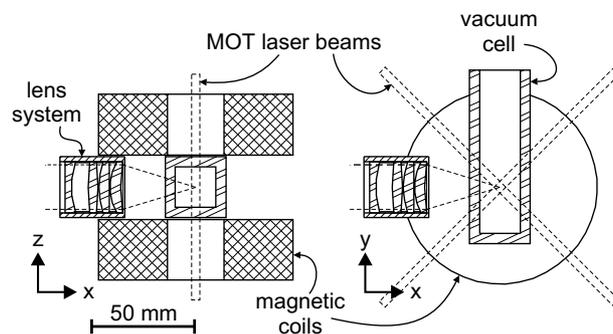


Fig. 1. Experimental geometry

between two magnetic coils. This results in the following typical requirements for an objective used for single atom experiments:

1. Collimation of the radiation of a point source at a wavelength of 852 nm with a large numerical aperture (NA). Once the light is collimated it can easily be imaged with low NA optics.
2. A minimum working distance of 36 mm. This is determined by our laser setup because laser beams reflected off the glass cell must not enter the objective. Moreover, the experimental geometry does not permit any optical elements inside the vacuum cell.
3. Near diffraction limited spot size on axis, to enable high resolution imaging and spatial filtering of the fluorescence light.
4. A field of view covering the MOT position uncertainty of about 1 mm^2 .
5. Imaging through a plane silica window of 5 mm thickness, which introduces spherical aberrations for a $\text{NA} > 0.2$.
6. Limitation of the outer diameter of the assembled lens system to 30 mm by the magnetic coils of the MOT, see fig. 1.

To keep the design reasonably simple and cheap, we restricted ourselves to spherical surfaces and BK7 glass only, and we used standard catalog lenses whenever possible.

Single spherical lenses exhibit a reduction of their resolution above a NA of about 0.1 due to their predom-

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inant spherical aberration. The main idea of a multi-lens system is therefore to compensate for the aberrations of one surface with the aberrations of other ones. In our case, positive spherical aberration from convex surfaces is the primary disturbance to eliminate. It needs to be balanced by negative spherical aberrations of concave surfaces.

The objective is designed using the program Oslo LT [4]. It traces a parallel input beam of fixed diameter through the lens elements and the 5 mm silica window. During the optimization the radius of curvature of the last surface of the last lens is controlled to keep the NA and effective focal length fixed. The program is set up to minimize the squared sum of the spherical aberrations up to 7th order and third order coma and astigmatism. The radii of curvature and the lens distances are used as variables, and the programs optimization routine is iterated. Different starting configurations are used in search for a global optimum.

Acceptable performance could not be achieved with three lenses, with four lenses, however, good designs were possible. The radii of curvature of the lens surfaces were subsequently fixed to catalog values of our vendor [5], each time reoptimizing the remaining variables. The resulting design is shown in table 1 and fig. 2. It consists of three standard lenses and one meniscus lens with catalog radii of curvature [6].

The design has a wavefront aberration of $\lambda/1000$ rms on axis, resulting in a diffraction limited spot size of $1.8 \mu\text{m}$ (airy disc radius). Provided that the curvature of the image surface is taken into account, the wavefront error at a distance of 0.5 mm off axis is $\lambda/13$ rms. 1 mm off axis the spot size radius increases to $3 \mu\text{m}$ rms.

Note that the performance of the objective is by no means limited to the special requirements of our experimental setup. Changing the distance between surfaces 2 and 3 in fig. 2 from 8.2 mm to 6.6 mm (and refocusing) allows the system to work even without the 5 mm silica window, with negligible performance degradation. Adaption to any window thickness up to 10 mm is possible.

Although the design is optimized for 852 nm it retains its diffraction limited performance from 1064 nm

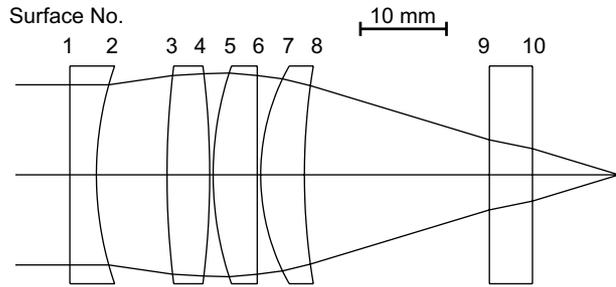


Fig. 2. Layout of the lens system. Surfaces 1 to 8 represent the objective itself, surfaces 9 to 10 represent the silica wall of the vacuum cell. The MOT is at the position of the focus on the right.

to 400 nm when the chromatic focus shift is taken into account.

3. Assembly and experimental tests

All lenses have a diameter of 1 inch, a surface quality (over 90% of the clear aperture) of $\lambda/4$, scratch-dig 20-10, centration <5 minutes of arc and AR-coating for 650–1000 nm. They are stacked into an aluminum tube of 1 inch inner and 30 mm outer diameter and held in place by a threaded retainer ring. The distances between the lenses are determined by thin aluminum spacer rings. The mechanical parts have been manufactured to a tolerance of 0.1 mm.

An experimental test of the wave front aberration was performed by focusing an 852 nm laser beam onto a $1 \mu\text{m}$ diameter pinhole serving as a high NA point source. The transmitted light was collimated by the objective under test and analyzed by means of a shear plate interferometer [7]. From the bending of the resulting interference fringes (fig. 3) we estimate a wavefront distortion of less than $\lambda/4$ peak-valley over 90% of the clear aperture.

In our MOT setup (fig. 1) the optical axis of the objective was carefully aligned onto the trap center using a Helium-Neon laser beam. The collimated fluorescence light from the MOT is focused by an $f = 80$ mm

Table 1. Specifications of the lens system.

Surface No.	Radius of curvature [mm]	Distance to next surface [mm]	Material
1	∞	3.08	BK7
2	39.08	8.20	air
3	103.29	4.97	BK7
4	-103.29	0.40	air
5	39.08	5.12	BK7
6	∞	0.40	air
7	26.00	5.07	BK7
8	78.16	21.55	air
9	∞	5.00	silica
10	∞	10.00	vacuum

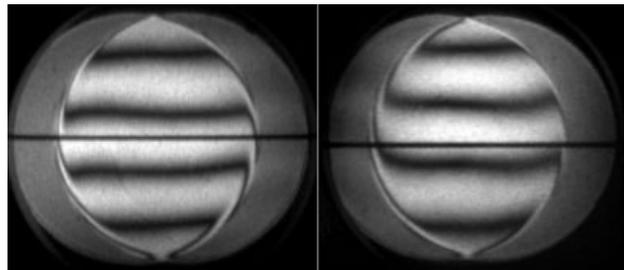


Fig. 3. Shear plate interferograms of the beam produced by collimating a point source with the objective lens. The shear is applied in two orthogonal directions, straight equidistant interference fringes correspond to a plane wavefront.

doublet lens through a pinhole of 150 μm diameter for spatial filtering (stray light suppression). The transmitted light is imaged onto an avalanche photodiode operated in single photon counting mode, with a quantum efficiency $\eta \approx 50\%$ at 852 nm. When the MOT lasers are saturating the atom, we detect about $8 \cdot 10^4$ fluorescence photons per second from one cesium atom on a stray light background of only $2.2 \cdot 10^4$ photons per second. Since with a NA of 0.29 we cover $\Omega/(4\pi) = 2.1\%$ of the total solid angle, and the lifetime of the excited state is $\tau = 30.5$ ns, the theoretical upper limit for the count rate of a strongly saturated two level atom is

$$R = \eta \frac{\Omega}{4\pi} \frac{1}{2\tau} = 17 \cdot 10^4 \text{ s}^{-1}. \quad (1)$$

Due to the more complex situation of a cesium atom in the MOT [8] the discussion of which is beyond the scope of this paper the expected value is significantly below the upper limit.

4. Conclusions

Using standard lenses we have successfully designed and built a diffraction limited, long working distance lens system for collecting fluorescence from single atoms in a MOT. The total cost of the objective including lenses and mechanical parts is about US \$ 500 only. A similarly inexpensive system could be advantageously used for high resolution imaging of single ions or atoms or for heterodyne detection of fluorescence

radiation. This system recently managed to detect single atoms in an optical dipole trap for the first time [9].

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