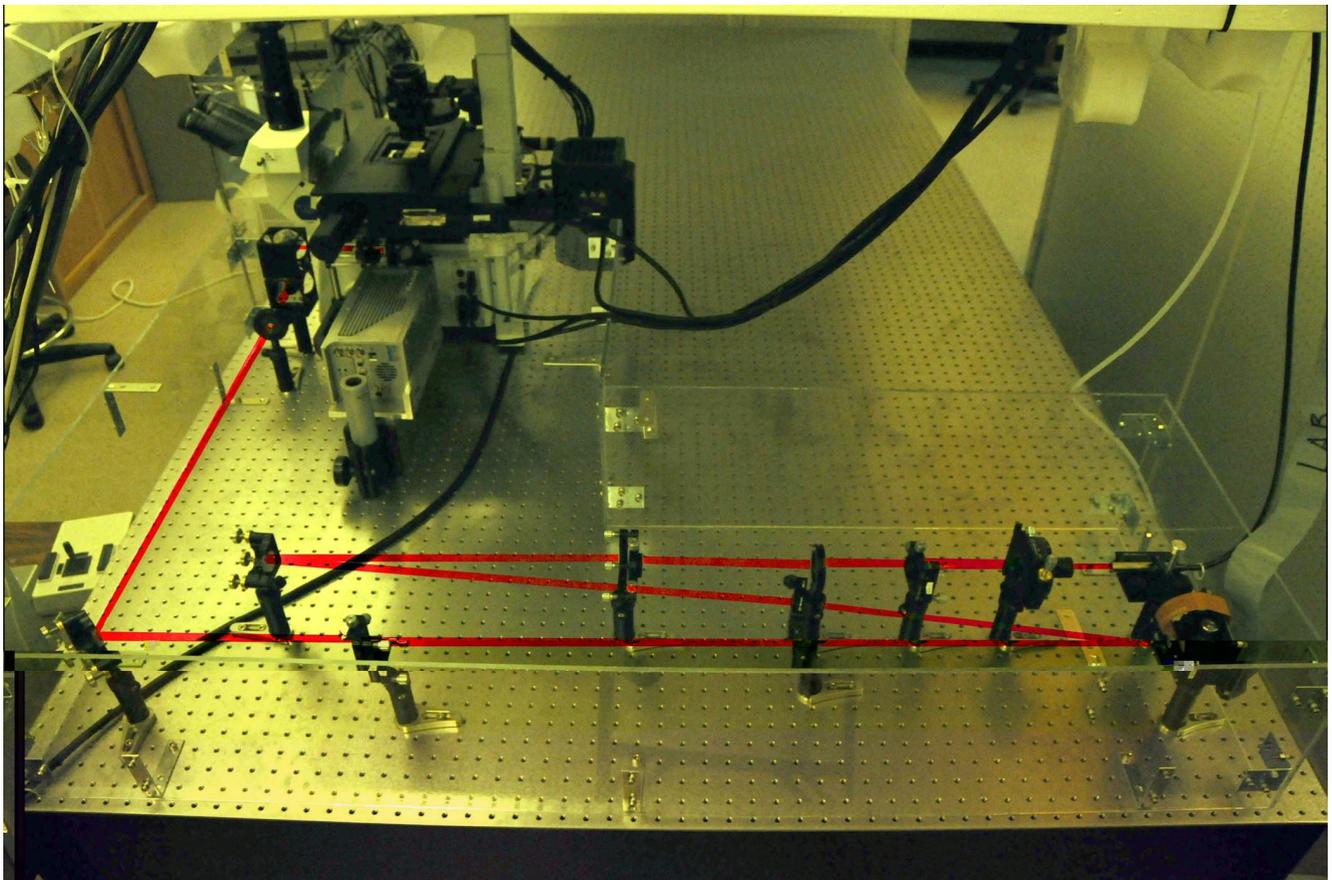


# The Design and Construction of a Holographic Optical Trap Based on a Liquid Crystal Spatial Light Modulator

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## **The Design**

The design of the holographic optical trap is based off of three main components. The components are a 1064nm Gaussian laser with a 5mm diameter, a Liquid Crystal Spatial Light Modulator (SLM) from Boulder Nonlinear Systems, and an Olympus Fluorescence Confocal Microscope. The basic principle of the system is that the laser is reflected off of the SLM into the objective of the microscope where it is tightly focused into the focal plane.

## **Background**

Trapping is achieved by the radiative force of the photons. When a particle, with a refractive index greater than the surrounding medium, typically a fluid, comes into contact with the beam it experiences two forces: (1) one due to the scattering of the light and (2) one due to bending of the light, the gradient force. The scattering force is caused by the photons that are reflected off the surface of the particle and is directly proportional to the intensity of the laser. The gradient force is caused by the Gaussian intensity distribution of the laser. When the particle is in contact with the laser, but not centered, the intensity distribution is not uniform over the particle and a net force towards the center of the beam is felt by the particle (see figure 2a). When the particle is centered, the particle enters a potential well and is trapped (see Figure 2b). The order of magnitude of these trapping forces are on the scale of piconewtons. The gradient force is proportional to the gradient of the intensity and must be larger than the scattering force in order for trapping to occur.

Holographic Optical Trapping, is achieved with a Spatial Light Modulator. The SLM is a liquid crystal display which can control, pixel by pixel, the intensity and phase of the reflected light. The SLM embeds a hologram which is then carried to the objective and reproduced around the focal plane of the objective. The SLM gives the user the ability to trap multiple particles in three-dimensional arrangements with a single laser. Also, the movement of each particle can be controlled with precision and without affecting the other trapped particles.

## Requirements

- The diameter of the laser has to be expanded to cover the entire surface of the SLM and then reduced to slightly greater or less than the diameter of the back aperture of the objective.
- The light incident on the SLM needs to be plane polarized with an adjustable orientation to achieve the maximum performance.
- The angle at which the laser is reflected off the SLM needs to be minimized to reduce the cross talk effects that occur when the light travels across more than one pixel region.
- The beam expander and the telescope must meet these criteria:
  - ~The ratio of the focal lengths has to be equal to the required magnification
  - ~The distance between each lens set has to be equal to the sum of the focal lengths
  - ~For the telescope, the distance from the SLM to the first lens and the distance from the second lens to the eyepiece of the objective have to be equal to the focal length of the first and second lens respectively.

## Restrictions

- The distance from the eyepiece of the objective to the laser port is 160mm.
- The largest focal length readily available is 1000mm
- Limited working space around laser port.

## Experimental Setup

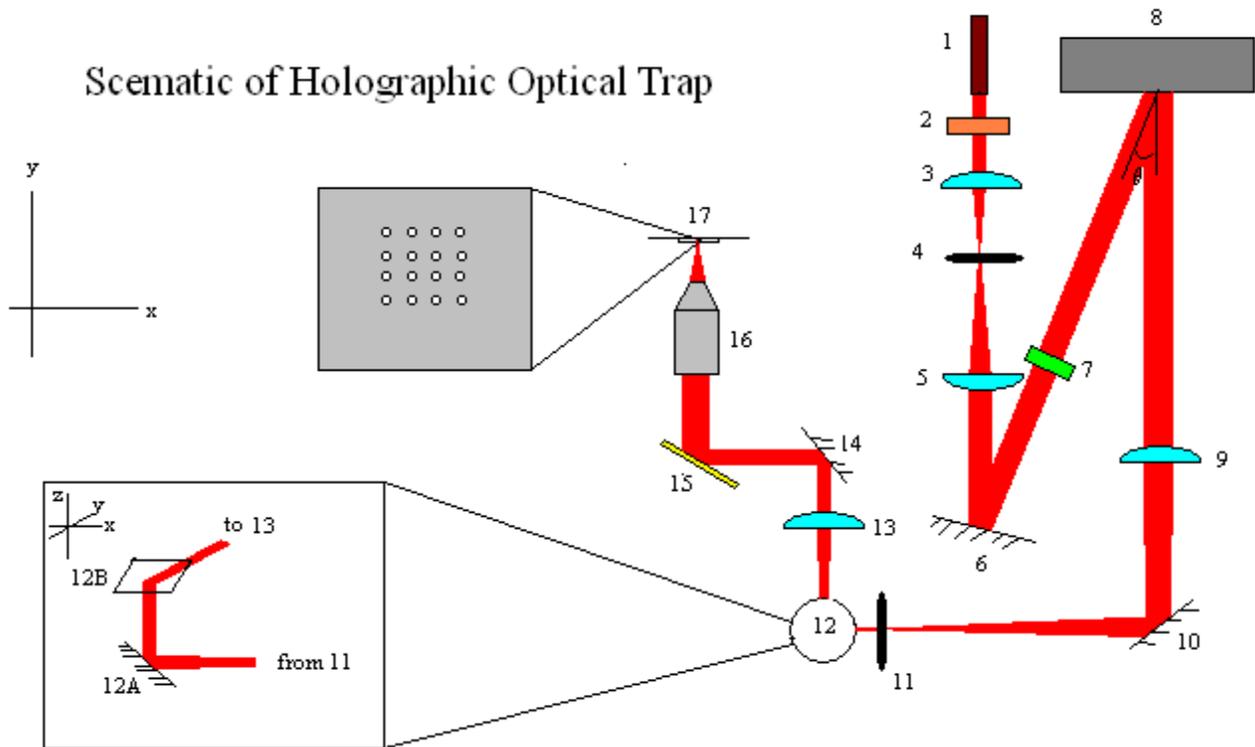
Taking into account the requirements and restrictions, the following design was produced.

Figure 1 shows the schematic of the trapping setup. Appendix B lists the details of the equipment used in the system.

The collimated laser, as it exits the optical fiber (1), is elliptically polarized at a random

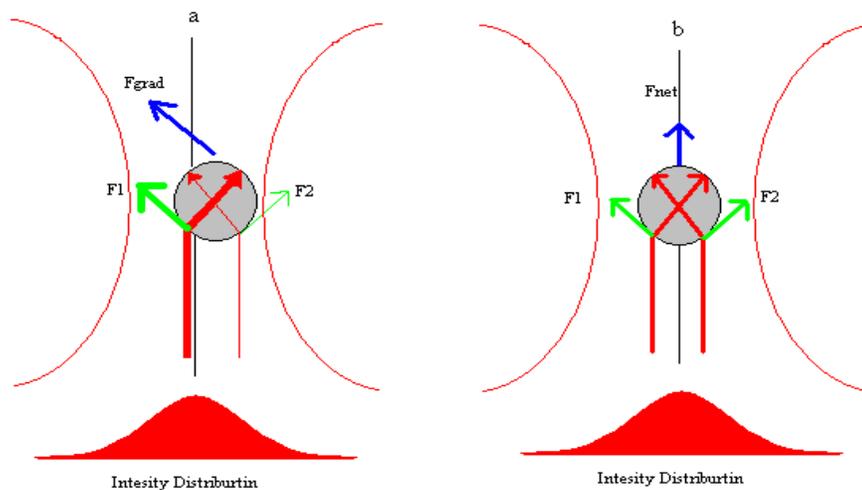
orientation. It first passes through a polarizing element (2) where it is reduced to plane polarized light. Next, the beam is expanded and collimated from the initial 5mm diameter to 12.4mm by the use of an expanding lens (3) with a 100mm focal length and a collimating lens (5) with a focal length of 250mm. The two lenses are positioned 350mm apart and an iris (4) is placed at the focal point between the two lasers, 100mm from the expander and 250mm from the collimator. The purpose of the iris is to remove any higher order diffractions and insure a clean Gaussian beam. The light is then reflected off a mirror (6) and sent through a  $\lambda/2$  wave plate (7) and onto the SLM (8). The  $\lambda/2$  wave plate has two purposes. The first purpose is to allow the user to control the orientation of the plane polarized light that is incident on the SLM, and second, to ensure that a clean plane polarized Gaussian beam reaches the SLM. Maximum intensity of the light reflected off of the SLM was obtained with the  $\lambda/2$  wave plate set at  $256^\circ$  on the rotation stage, and the polarizing element at  $298^\circ$  for the single trap setting of the SLM. The angle between the incident and reflected light off of the SLM is roughly  $8^\circ$ . The desired angle is  $5^\circ$  but at that angle the mount for the  $\lambda/2$  wave plate blocks the path of light. After the SLM, the laser travels 1000mm to the first lens of the telescope (9) with an equal focal length. A mirror (10) then reflects the light by  $90^\circ$ . At a distance of 1000mm from the first lens of the telescope, another iris (11) is placed to again remove and higher order diffractions that might have been produced along the path and ensure a clean Gaussian beam. At this point the laser enters the periscope (12). The periscope raises the beam (12A) to the level of the optical port on the microscope and turns the beam by  $90^\circ$  (12B). The second lens of the telescope (13) is the next optical component. It has a focal length of 300mm and is placed 1300mm from the first lens of the telescope and 300mm from the eyepiece of the objective. The telescope reduces the diameter of the lens from 12.4mm to 3.9mm. The final two components are a mirror (14) which directs the laser  $90^\circ$  into the laser port of the microscope and a dichroic mirror (15) reflects the beam into the objective (16). The final lens and mirror are held in a Thor Labs 30mm cage system that was used for its size, but this cage system is limited to a single plane so we switched to the Newport cage system for the periscope.

## Schematic of Holographic Optical Trap



**Figure 1:** The schematic of the holographic optical trapping system. The laser travels through an optical fiber (1) to the optical table. The light is then polarized (2), expanded (3) and collimated (5). A mirror (6) is used to redirect the light which then passes through a half-wave plate (7) and then is reflected off of the SLM (8). The laser then travels through the first lens of the telescope (9), redirected off another mirror (10) and enters the periscope (12). The periscope translates the laser vertically (12A) as well as horizontally (12B). After the change in height and direction, the laser passes through the second lens of the telescope (13), directed into the microscope (14), reflected off a dichroic mirror (15), enters the objective (16), and then it is tightly focused onto a sample (17).

Optical Trapping Force Diagram



**Figure 2:** Force diagram caused by the bending of the light in the particle. (a) when the particle is not centered over the beam, and (b) when the particle is centered

## Acknowledgments

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## References

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## Appendix A

### Alignment Procedure

NOTE: All numbers refer to the diagram in Figure 1.

Make sure the translation stage is set to one and that the laser port aperture is open before checking alignment.

Use the 622nm guide laser

- Close the first iris (4) and check if the laser is centered and whole. If it is not centered check and adjust, if needed, parts 1,2, and 3. before moving on make sure the edges of the laser beam have not been trimmed by the polarizer (2).
- Check if the beam covers the entire surface of the SLM. If it is not adjust mirror 6.
- There are two targets with pinholes the sit in the Thor Labs cage. Place one at the closest end of the cage and press against the cage stand to make sure it sits square. Place the second target against the the mirror mount (14).
- Adjust mirrors 10 and 12B so that the laser passes through the pinholes of both targets. Due to the design of the Newport cubes, mirror 12A has to be assumed fixed and cannot be used for alignment. The periscope was initially aligned independent of the rest of the system, and mirror 10 and 12B are used to align the laser to mirror 14.
- Close the second iris (11) and check if the laser is **roughly** centered. If the laser is not roughly centered than the periscope has rotated. If this is the case then:
  - ~ readjust the alignment screws of mirror 12B so that they are all about halfway tightened and adjust mirror 10 so that it is centered on the iris.
  - ~ rotate the periscope until the laser is close to the pinhole of the first target
  - ~ adjust mirror 12B so the laser enters the pinhole
  - ~ now fine tune mirrors 10 and 12B so the laser passes through both pinholes
- Rotate the objective stage to an open port and remove the cap.
- Adjust mirror 14 so that the laser is roughly centered. By this point the guide laser is very dim so pay close attention. There are three alignment screws for mirror 14. Two of them have knobs and the third one takes an Allen wrench. You will need to use this alignment screw so don't forget that its there.
- At this point you should be able to find the beam in a sample.
- Place a sample on the microscope with the 60X or 100X objective, focus into the slide, find the guide laser, and adjust mirror 14 until it is centered **in the field of view of the camera.**
- Turn on the IR laser and trap a particle. The IR is not guaranteed to be exactly at the same point as the guide and the final fine tuning is achieved indirectly by centering the trapped particle.

**If you are not sure of the cause of the alignment error start from scratch, and make sure the laser remains at the same height above the table all the way to the periscope.**

## Appendix B

### Equipment and Hardware

Note: All numbers refer to the parts labeled in Figure 1

- 1) Laser and Fiber – Photonics IPG 1064nm Fiber Laser with 622nm guide  
Model: YRL-10-1064  
SN: PL080478
- 2) Glan-Laser Calcite Polorizer\* – 1064nm Polarizing element  
Model: 106L08AR.33
- 3) Expanding Lens\* - 100mm focal length
- 4) Iris\* - with adjustable aperture  
Model: ID-1.0
- 5) Collimating Lens\* - 250mm focal length
- 6) Mirror\*\* - Silver coated with 1 inch diameter and 98% reflection for 1064nm light  
Model: PF10-03-P01
- 7)  $\lambda/2$  waveplate\* -  
Model: 10RP12-35
- 8) XY Phase Flat 512 Spatial Light Modulator (SLM) - from Boulder Nonlinear Systems  
SN: 7927
- 9) Telescope Lens 1\* - 1000nm focal length
- 10) Mirror\*\* - refer to (6)
- 11) Iris\* - refer to (4)
- 12) Newport cage system cubes\* - chosen for XYZ control of the beam
- 12A) Mirror\*\* - refer to (6)
- 12B) Mirror\*\* - refer to (6)
- 13) Telescope Lens 2\* - 300nm focal length
- 14) Mirror\*\* - refer to (6)
- 15) Cromax Dicroic Mirror - see specifications from Cromax  
Model: z900dcsp 207691

\* Purchase from Newport

\*\* Purchased from Thor Labs

**- All lenses are Plano-convex with a 1 inch diameter and 1064 anti-reflective coating**

-Lenses 3, 5, and 9 are held by Newport 5-Axis Lens Positioner.

Model: LPU-1

-Lens 13 is held by Thor Labs XY Adjustable Carriage for 30mm cage system

Model: HPT1

- Mirrors 6 and 10 are held by Newport 3-Axis Mirror Mounts.  
Model: V-100 A3K
- Mirrors 12A, and 12B are held by Newport mirror mounts designed for the Newport cage system.  
Model: Q-SS100-R3HN
- Mirror 14 is held by Thor Labs Right-Angle Kinematic Cage Mount for 30mm cage system.  
Model: KCB1
- $\lambda/2$  waveplate, 7, is held by Newport RSP Series Rotation Stage  
Model: RSP-1T
- Polarizer, 2, is held by Newport 481 Series Rotating Stage  
Model: 481-A-S