



The Science of Optical Trapping

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The basic physical principles that make optical traps possible are not very complex. Understanding how and why optical trapping works will help you to better control your experiments and the BioRyx® 200 system. This document covers the basic physical concepts behind optical trapping and explains how the BioRyx® 200 system works. Using this background, we then discuss techniques you can use for various types of samples and applications. This document covers the following topics:

- I. The Light Wave
- II. Dielectrics
- III. Trapping Matter with Light
- IV. Absorption, Scattering and Transmission of Light
- V. Laser Basics
- VI. Further Thinking About Optical Traps
- VII. Optical Trapping Techniques

I. The Light Wave

Light and Electromagnetic Fields

A fundamental property of light is that it consists of oscillating electric and magnetic fields. These fields carry the light's energy and are responsible for the interaction of the light with material. The fields are transverse (perpendicular) to the direction in which the light is traveling, as shown to the right. In the figure on the right, the light ray is traveling to the right. As the light travels, the electric field (**E**) oscillates along the vertical direction while the magnetic field (**B**) oscillates in and out of the page.

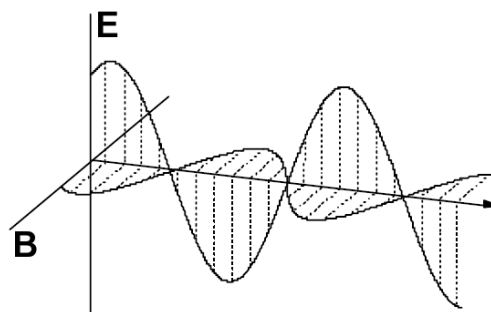


Figure 1

Wavelength and Color

The wavelength, λ , of light is the distance the light must travel for its electric field to oscillate from its maximum value to its minimum value and back to its maximum value. Thus, Figure 1 shows the fields over about 1.5 wavelengths of travel. The wavelength of light is what we perceive as color. Table 1 shows the wavelengths corresponding to various colors of light.

Table 1—Wavelength of Light

Color	Approx. Wavelength (nm)	Approx Frequency (tera Hertz)
Ultraviolet	10-350	30000-857
Blue	475	632
Green	530	566
Yellow	590	508
Orange	610	492
Red	700	429
Infrared	780-700,000	385-0.4.29

Light and Energy

The energy of light is inversely proportional to its wavelength. For example, blue light has more energy than red light, since red corresponds to a longer wavelength. Another way to describe this relation is in terms of frequency. The frequency of light, i.e. the rate at which the electric field oscillates, is inversely proportional to the wavelength. The energy of light is therefore proportional to its frequency.

The intensity of light describes the amount of energy that passes through an area in a given amount of time. To increase the intensity, one typically increases the output of the light source or else focuses the light into a smaller region.

II. Dielectrics

A Close Look At Matter

The atoms and molecules which comprise a material are typically electrically neutral. Although the material consists of a large number of positively charged protons and negatively charged electrons, the net electric charge is zero. Furthermore, the positive and negative charges within the material are uniformly distributed. If one thinks of a single atom, this corresponds to the negative electrons being symmetrically distributed around the positive nuclear charge.

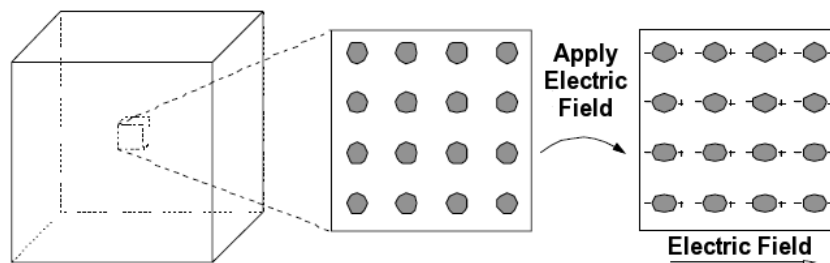


Figure 2

Polarization of a Dielectric

The strength of the polarization increases with the strength of the applied electric field. The stronger the applied field, the more charge is drawn to the ends of the atom or molecule. The quantity that indicates the degree of charge separation is known as the electric dipole moment. When the external electric field is turned off, the charges return to their former symmetric and uniform distribution. Materials which behave this way are called non-polar dielectrics.

Some molecules, such as water, have intrinsic dipole moments due to their atomic structure. These materials are referred to as polar dielectrics. When a polar dielectric is placed in an electric field, the field tends to orient the molecules such that their dipole moments align in the electric field. Thermal motion of the molecules tends to randomize their orientation. Thus, the amount of alignment varies with temperature.

The Dielectric Constant

When a material is polarized by an external field, the many aligned dipoles within the material produce an internal electric field that opposes the externally applied field.

The strength of the internal field depends upon the material properties and the strength and frequency of the externally applied field. The material properties are captured in a single parameter called the dielectric constant, k . A vacuum has a dielectric constant of $k=1$, since it has no atoms to shield the externally applied field. In general, as the frequency of the applied field is increased, the dielectric constant decreases because the molecules have a harder time "keeping up" with the rapid field oscillations. Polar substances, such as water, tend to have high dielectric constants at low frequencies. For our purposes, the important parameter is the

dielectric constant of the material at optical frequencies. The dielectric constants of some common materials are given in Table 2. Values are shown both for a static applied field (DC) and for a field at optical frequencies. It should be noted that the dielectric constant for a material is often given via a related quantity, the index of refraction. The index of refraction is the square root of the dielectric constant at optical frequencies.

Table 2--Dielectric Constants of Common Materials

Material	Dielectric Constant k (DC)	Dielectric Constant k (Optical)
Vacuum	1	1
Air	1.0005	1.00005
Mineral Oil	2.24	2.22
Polystyrene	2.6	2.4
Pyrex	4.7	2.17
Ethanol	2.5	1.85
Water (25 °C)	78.5	1.78
Water (20 °C)	80.4	1.78
Silica	3.8	2.1

III. Trapping Matter with Light

Interaction of a Dipole with an External Electric Field

An electric dipole experiences an alignment force when placed in an external electric field. Additionally, the entire dipole experiences a force in the direction of increasing electric field strength. The magnitude of the force is determined by how quickly the electric field changes in space. If nothing prevents the motion of the dipole, it will move to the region of maximum electric field strength.

Optical Traps for High Dielectric Objects

In most cases, the object one may want to manipulate with an optical trap has a higher dielectric constant than its environment. An example of this would be a polystyrene ($k=2.4$) sphere in water ($k=1.78$). To trap the sphere, we need to create a small region with very high electric field strength which falls off quickly at the edges. One way to do this is to focus a beam of light into a very narrow and intense spot by using a high-power lens like a microscope objective lens.

In this case, the electric field used to trap the object is the electric fields associated with the beam of light. We refer to this localized region of very high light intensity as an optical trap. Any object that has a higher dielectric constant than the surrounding material--such as the polystyrene sphere in the example above—and that enters the optical trap, will become trapped.

Optical Trap Strength

The ability of an optical trap to hold an object in place or move it around depends on the strength of the trap. The following properties determine the trapping force:

- **Dielectric constant:** For most materials, the larger the difference between the object's dielectric constant and the dielectric constant of its environment, the stronger the trap will be. For very large dielectric constants, radiation pressure begins to dominate and the traps begin to weaken. Good trapping is usually possible for objects that have a dielectric constant that is between 1.1 to 2.25 times higher than the dielectric constant of the surrounding medium.
- **Trap intensity:** Higher-intensity light in the trap will create a stronger trap.
- **Trap gradient:** The gradient is the rate of change in light intensity as one goes away from the center of the trap. If the light intensity drops off very quickly with distance from the center of the trap, the trap will be much stronger.

If a trap is not strong enough, the trapped object may escape from the trap due to random thermal motion (Brownian motion) or external forces such as drag force from flow of the surrounding medium, or gravity.

IV. Absorption, Scattering, and Transmission of Light

Absorption and Heating

Some of the light in the optical trap is absorbed by the material in the trap. The exact amount of absorption depends upon the material in the trap and the intensity of the trap. The absorbed light may heat up the object in the trap dramatically because the intensity of the light inside the trap is extremely high. For example, because of the low absorption of visible light by silica, heating effects are unimportant for most trapping purposes.

Transmission

If the sample is transparent, most of the light from the optical trap is transmitted through the sample. Trapping is possible as long as the light is refracted by the sample. This occurs as long as the dipole moment of the medium is sufficiently different from the dipole moment of the sample to be trapped.

Scattering

The term "scattering" refers to a number of different processes whereby light interacts with material and changes direction. In some cases, other properties of the light such as its wavelength or polarization will also be changed. In general, light may be scattered in any direction from the sample.

V. Laser Basics

What Is a Laser?

Lasers today are very commonplace and come in many varieties. However, all lasers share some common characteristics. Central to the operation of a laser is the notion of light amplification. Lasers take a little bit of "seed" light and amplify the light greatly by converting some external energy source, such as electricity, into additional light. Another important feature of lasers is that the light coming out is highly collimated. Most commonplace sources of light emit radiation uniformly in all directions. Collecting all of this light and focusing it into a narrow beam increases the intensity of light enormously (a factor of one million at a distance of one meter).

Using Lasers For Optical Traps

Both amplification and collimation result in a high-intensity source of light, which is a critical feature for creating optical traps. Most realizations of optical traps achieve even higher field intensities by focusing the laser through the objective lens of a microscope. This implementation creates a high-intensity spot in the viewing plane of the microscope. Typical intensities are around 10^6 W/m².

Another feature of lasers which is important for Arryx's holographic optical trapping (HOT) technology is beam coherence. The amplification mechanism for most lasers results in a beam whose constituent light waves are all moving together in phase. This is critical for the process of using holograms to control optical traps.

Holographic Optical Traps

The BioRyx® 200 system employs a spatial light modulator to sculpt the light from the laser into as many as 200 independently controllable optical traps. The spatial light modulator consists of a liquid crystal display element which modifies the phase of the coherent laser beam in order to create user-defined, three-dimensional patterns of optical traps. The ability to sculpt the beam in this manner also allows the user to create traps which have non-standard beam profiles, allowing for stronger, more numerous, and more versatile traps than are available with traditional optical trapping systems.

VI. Further Thinking About Optical Trapping

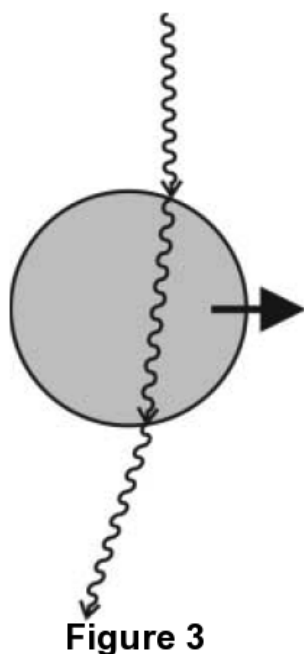


Figure 3

Light and Momentum

In the description above, light was treated as a wave. Light can also be thought of as a stream of photons which carry both energy and momentum. Photons striking the surface of an object transfer some of their momentum to that object. This effect, known as radiation pressure, is much like the force exerted by the stream of water from a fire hose pointed at an object. However, radiation pressure is a much weaker force and is usually unnoticeable on macroscopic objects.

Conserving Momentum of Scattered Light

The previous explanation for the trapping effect of an optical trap relies on consideration of the change in energy of the light beam as a dielectric particle enters the beam. It is also possible to understand trapping from a momentum point of view. As a spherical particle is displaced from its central position in the trap, it bends light, much as a lens does, as illustrated in Figure 3. The bending of the light means that a momentum component away from the trap has been introduced into the light beam. In order to conserve momentum, the sphere must therefore be deflected back into the focal point of the trap, and it is clear again that the focused beam of light will serve to contain the particle.

VII. Optical Trapping Techniques

Simple Optical Trap

The most straightforward optical trapping method involves using highly focused beams of light to grab particles or cells. Each beam grabs and manipulates a single object.

Using Boundaries

The ability to create multiple traps allows for unique trap implementations. For example, a tightly spaced circle of traps can be generated in order to serve as a corral for containing particles. Optical traps in the corral can be turned on and off briefly to serve as doors to the corral for introducing or removing particles.

Optical Trap Nets

Grabbing biological specimens with optical traps carries a risk for injury to the specimen resulting from heating by the highly focused beam of light. Trap nets enable a "bed of nails" approach, in which a number of weaker traps are combined to work together in manipulating objects. Trap nets also allow motile objects to be captured by distributing a large number of traps and increasing the likelihood that the object wanders into one or more of the traps. Trap nets also make possible adroit manipulations of objects because the multiple traps can rotate as well as translate objects.

Trapping Materials with a Small Dielectric Constant

One of the disadvantages of standard optical traps is that the trapping mechanism relies on the fact that the dielectric constant of the trapped particle is higher than that of the surrounding medium. Particles that have a dielectric constant lower than the surrounding medium are repelled from the focused light. The BioRyx® 200 system implements a form of trap called an optical vortex, which is basically a hollow shell of light, which forms a container for the particle. The particle is repelled from the walls of the light container, trapping the particle.

Three-Dimensional Optical Trapping

The BioRyx® 200 system enables translation of trapped objects in the third dimension in addition to motion in the imaging plane. Since many objects of interest have higher density than their surrounding medium, sedimentation is common. Three-dimensional control allows trapped objects to be lifted over sedimented neighbors.