Optical trapping induced by nonlinear reorientation of liquid crystals

Francesco Simoni, Liana Lucchetti, Luigino Criante, Francesco Bracalente, and Francesco Aieta

Optical nonlinearity can drive particle trapping under unconventional conditions, with implications for work in biological environments.

The increasing interest in optical manipulation, i.e., methods to control the movement of microsized particles by light beams, is being driven by the wide spectrum of possible applications in biotechnology. Indeed, the micron size of typical cells is a good match for the usual focusing-spot size of conventional optical tweezers. Consequently, cells can be trapped and moved by light to study their functionality or to induce specific processes (e.g., DNA modification). These and other possible advances in optical manipulation make it interesting to investigate optical trapping of particles dispersed in liquid crystals. In fact, the strong optical anisotropy of these materials makes them an ideal test bed for optical trapping in an anisotropic (i.e., the physical properties are different in different directions) environment, a common condition when dealing with biosystems.

In performing such an investigation, a few years ago Mu-sevic and his co-workers\(^1\) pointed out that trapping particles dispersed in nematic liquid crystals is possible even when the refractive index of the particles is lower than that of the liquid crystals: \(n_p < n_{o,LC} < n_{e,LC}\) (where \(n_p\) is the refractive index of the particle, \(n_{o,LC}\) is the ordinary refractive index of liquid crystal, and \(n_{e,LC}\) is the extraordinary refractive index of liquid crystal). This is an important discovery because the phenomenon occurs under conditions that prevent the onset of trapping gradient forces requiring \(n_p > n_{\text{environment}}\).

Musevic further suggested\(^1\) that an important role in this unconventional trapping is played by optical reorientation of liquid crystals, that is, by realignment of molecules induced by the laser light. Optical trapping would occur as a consequence of this local reorientation. In fact, the elasticity of the medium induces the movement of the particle to minimize the free energy of the system. A similar effect showing attractive forces is known to occur between two colloids in an anisotropic environment. Here we report a strong relationship between the nonlinear optical properties of nematic liquid crystals and the strength of the trapping forces, under conditions that are forbidden for conventional optical trapping.\(^2\)

We took a conventional optical tweezers apparatus in the inverted microscope configuration and equipped it with a second, weak laser beam acting as a probe for the optical reorientation of liquid crystal molecules induced by the more powerful trapping beam. This allowed us to track particles in the normal way, obtain their position and speed, as well as measure the nonlinear optical phase shift due to molecular reorientation as given by the probe beam.

In carrying out the measurements, we varied the optical power of the trapping beam and the type of samples, all of which had different optical nonlinearities. In particular, we compared the behavior of samples containing the undoped nematic liquid crystal 5CB with that of the samples containing 5CB doped by...
Figure 2. Speed of the trapped particle vs. time. (top) Undoped liquid crystal sample. (bottom) Sample doped by azo-dye with enhancement of the nonlinear optical response. Different colors refers to different powers of the trapping beam. $v$: Velocity. $t$: Time.

the azo-dye Methyl Red. This is known to enhance the nonlinear properties of liquid crystals by orders of magnitude.

Figure 1 reports the speed of the trapped particle together with the nonlinear induced phase shift measured at the same power. The tight relationship between the trapping conditions and the nonlinear reorientation is clearly shown: the speed increases as the nonlinear reorientation does, until saturation occurs. Figure 2 shows a similar connection to the nonlinear optical properties. For the doped sample with higher nonlinearity (bottom), the speed is one order of magnitude higher than for the undoped (top) sample, and the required power one order of magnitude lower. All the experimental data confirm that optical reorientation drives optical trapping in liquid crystals under forbidden conditions. A more quantitative description of the results raises the need to address the new problem of studying nonlinear reorientation of liquid crystals under strong focusing conditions, which has yet to be investigated.

More broadly, a light-induced defect in a previously ordered structure causes particles to be attracted toward the defect in the presence of long-range molecular interactions. This issue is related to recent work on singularities induced by light beams,\(^3\) which has potential interest for micropatterning and device fabrication. Next, we will study how extreme focusing conditions affect the nonlinear optical reorientation of liquid crystals, which is responsible for optical trapping, and how to exploit these nonlinearities for active control of trapping strength.

Author Information

Francesco Simoni, Liana Lucchetti, Luigino Criante, Francesco Bracalente, and Francesco Aieta
Università Politecnica delle Marche
Ancona, Italy

Francesco Simoni is full professor of physics and fellow of the Optical Society, Italy. He is presently chair of the European Cooperation in Science and Technology MP0604 action Optical Micro-Manipulation by Nonlinear Nanophotonics (2007–2011), a network involving groups from 18 European countries and Australia.

References