

The resolution of optical traps created by Light Induced Dielectrophoresis (LIDEP)

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Abstract: Light induced dielectrophoresis (LIDEP) is a variant of the dielectrophoresis (DEP) mechanism that has been used for some time to manipulate particles in a microfluidic environment. Rather than relying on lithographically created contacts to generate the required electrical fields, the electrical contacts in LIDEP are created through the selective illumination of a photoconductor. The key question we address is how microscopic traps created via LIDEP compare to optical traps based on the gradient force, in terms of power required and trap stiffness achieved, as well as the size resolution of such a trap. We highlight the complex interplay between optical power and resolution with electrical parameters, such as the electrical resistance and applied AC Voltage. We show that for a spot size of five micrometres and larger, particles can indeed be trapped with low power. We use trap stiffness per mW to compare LIDEP with an optical trap and show that our system is 470 ± 94 times stiffer per mW than a conventional optical trap, with no loss of resolution. We also discuss the difficulties of achieving trapping at smaller spot sizes, and that the sub-micron resolution possible with gradient force trapping is very difficult to realise with LIDEP.

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References and links

1. H. A. Pohl, *Dielectrophoresis* (Cambridge University Press, Cambridge, 1978).
2. P. Y. Chiou, A. T. Ohta and M. C. Wu, "Massively parallel Manipulation of single cells and microparticles using optical images," *Nature* **436**, 370-372 (2005).
3. P. Y. Chiou, A. T. Ohta and M. C. Wu, "Toward all optical lab-on-a-chip system: optical manipulation of both microfluid and microscopic particles," *Proc. SPIE* **5514**, 73-81 (2004).
4. A. T. Ohta, P. Y. Chiou and M. C. Wu, "Optically-controlled manipulation of live cells using optoelectronic tweezers," *Proc. SPIE* **6326**, 632617 (2006).
5. K. Dholakia and P. Reece, "Optical micromanipulation takes hold," *Nano Today* **1**, 18 (2006).
6. A. T. Ohta, P. Y. Chiou, H. L. Phan, S. W. Sherwood, J. M. Yang, A. N. K. Lau, H. Y. Hsu, A. Jamshidi, and M. C. Wu, "Optically controlled cell discrimination and trapping using Optoelectronic Tweezers," *IEEE J. Sel. Top. Quantum Electron.* **13**, 235-243 (2007).
7. Y. S. Lu, Y. P. Huang, J. A. Yeh, C. Lee and Y. H. Chang, "Controllability of non-contact manipulation by image dielectrophoresis," *Opt. Quantum Electron.* **37**, 1385-1395 (2005).
8. K. Svoboda and S. M. Block, "Biological applications of optical forces," *Annu. Rev. Biophys. Biomol. Struct.* **23**, 247-285 (1994).
9. M. P. Hughes, *Nanoelectromechanics in Engineering and Biology*, (CRC Press, 2003).
10. Particle trapping software developed by Graham Milne based on the pattern matching capabilities built into LabVIEW.

1. Introduction

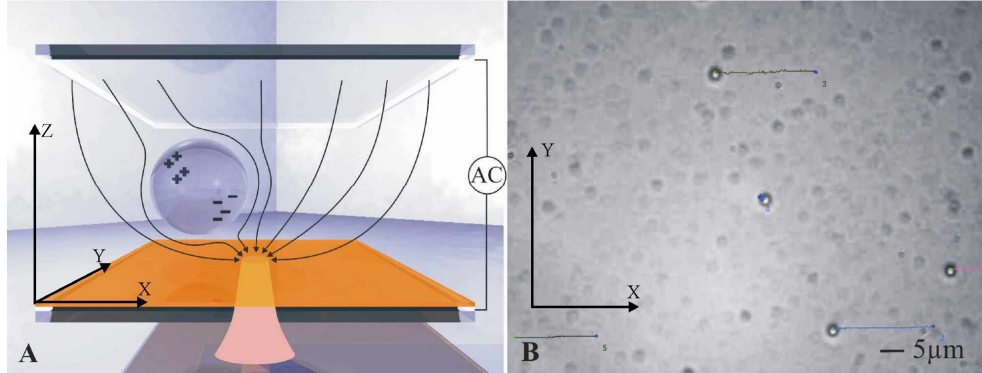


Fig. 1. (A). Diagram of a LIDEP chamber. The chamber consists of two plates with an AC Voltage applied across them. The arrows show the electric field resulting from the resistivity change caused by the illumination of the photoconductive plate. (B). A still from a movie showing the paths of trapped and non-trapped particles, the trapped particle being in the center. The plates are moved along the x axis with respect to the laser causing any particle not trapped to move horizontally with respect to the camera, indicated by horizontal lines.

An electrically neutral but polarizable particle situated in a non-uniform electric field will experience a force due to the interaction of the dipole set up within the particle and the field that created it. This force, termed dielectrophoresis, (DEP) was first described by Pohl in 1951 and has since become a popular force for the manipulation of micron sized particles especially since the publication of his book in 1978 [1]. Most dielectrophoresis experiments use microfabricated electrodes to create the electrical field gradients that cause the DEP force. Recently it has been shown that similar gradients can also be created by selectively illuminating a thin film of photoconductive material [2-4]. The illuminated pattern creates a ‘virtual electrode’ which offers the advantage of continuous control. By changing the light pattern it is possible to change the pattern of the DEP force, hence we refer to this mechanism as “Light induced Dielectrophoresis” (LIDEP). LIDEP affords control over micron-sized particles similar to the Optical Trapping (OT) mechanism based on the gradient force [5] except that it requires much less optical intensity. LIDEP can therefore create up to 15,000 traps with just 1mW of light [2]. The geometry is shown in Fig. 1(A). A LIDEP chamber consists of a liquid layer sandwiched between two conductive plates, one coated with the photoconductor, which is usually amorphous silicon (a-Si). An AC is passed between these plates creating an electrical field in the z direction. When the chamber is not illuminated most of the voltage is dropped across the photoconductive layer, however when it is illuminated the increased conductivity causes most of the voltage to be dropped across the liquid. The electrical field in the liquid has high field gradients around the illuminated area. With positive DEP this pulls the particle towards the surface, keeping it in an area of high field gradient so that when the illuminated spot is moved in the x and y plane the particle follows it.

LIDEP has also been performed on a single substrate without the need for a second conductive plate [6], using an array of interdigitated a-Si electrodes that are optically addressed. The single substrate simplifies the integration of microfluidic channels, however the resolution is reduced to the pitch of the electrodes (here 30 μm).

Apart from requiring less optical power than optical trapping, LIDEP trapping has the further advantage of being frequency dependent (see appendix) thus offering an additional degree of freedom for manipulating and sorting particles in a microfluidic flow. Small low

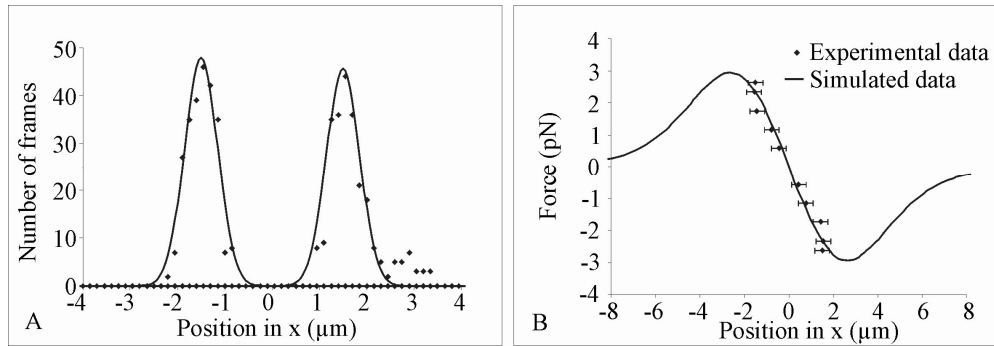


Fig. 2. (A). When the chamber is moved with respect to the optical spot, the trapped particle experiences a dynamic equilibrium at a specific position given by the balance of the trapping force and the drag force exerted by the moving liquid. This position follows a Gaussian distribution around a point to the right of the trap center when the chamber is moved to the right and vice versa. The example shown was taken for a chamber velocity of $4.5 \mu\text{ms}^{-1}$ (B). Each velocity corresponds to a force that is plotted against the center of the Gaussian position distribution (using the sigma value of the Gaussians as a measure of the error in position). This is compared with simulated data. The graph shown in A corresponds to the two extreme points (at $\approx 1.6\mu\text{m}$ position) in B.

conductivity particles, for example, feel a positive force (towards an area of high field intensity) at low AC frequencies and a negative force (away from areas of high field intensity) at high AC frequency. The point at which the force crosses over differs for particles of different conductivity, which can therefore be used to discriminate between these, e.g. live and dead cells or different types of live cells [2-4, 6].

A previously published method of characterising LIDEP was to measure the distance from the trap center at which particles no longer experience a force [7]. This gives useful insights, but does little to show what happens within the trap itself. The traps studied were also very large, of order $25\mu\text{m}$ illuminated area, leaving the question of the smallest possible trap size open. It was also shown that a $4.5\mu\text{m}$ size colloidal particle can be manipulated using negative dielectrophoresis [2] but not yet with positive dielectrophoresis, which is much more convenient, as it attracts particles to areas of high intensity. Other work on investigating the resolution and power dependence of LIDEP [3] showed that with a $17\mu\text{m}$ optical spot and $8 \mu\text{W}$ optical power, the peak force on the particle is situated $6\mu\text{m}$ from the trap center while with $800\mu\text{W}$ optical power, the peak force occurs $16\mu\text{m}$ from the center. The same paper also suggests that the minimum spot size is only dependent on the diffraction limit of the optical pattern and the diffusion length of the charge carriers in the material. Here, we show that other factors need to be taken into account that limit the size of the trap. We show that if the illuminated conductivity of the a-Si is too high, the trap will always be larger than the optical spot. We also show how reducing the trap size to below $5\mu\text{m}$ can adversely affect the electrical properties, resulting in a reduced trapping force.

2. Experimental

A $2\mu\text{m}$ thick layer of amorphous silicon (a-Si) was used as the photoconductor. The silicon layer was deposited by PECVD from a silane/hydrogen mixture onto ITO coated glass. 20nm of silicon Nitride was then deposited by e-beam evaporation to provide an insulating layer that blocks any DC voltage. The LIDEP chamber is then created by sandwiching a mixture of $100 \mu\text{m}$ and $2\mu\text{m}$ diameter colloid between this plate and a second ITO coated plate. The $100\mu\text{m}$ diameter colloid acts as a spacer to keep the plates apart and to allow the $2\mu\text{m}$ diameter colloid to be used as analyte. The applied AC Voltage was 8V peak-to-peak at 2kHz , which results in a positive DEP force. The illumination is provided by a 670nm laser

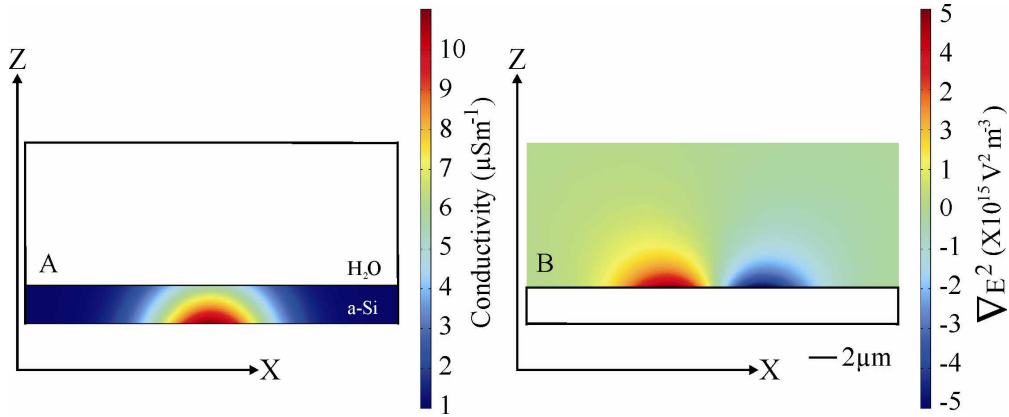


Fig. 3. (A). The conductivity of the a-Si can be seen to vary in a Gaussian profile in the x direction to account for the profile of the laser beam. B) Shows the gradient of the electric field in the x direction squared, which is proportional to the DEP force.

pointer which is expanded through a telescope before being focused by a 20x objective (N.A. 0.42, Nikon). The beam is attenuated by neutral density filters to 40μW, measured after the objective, and the spot size was measured as 4.9μm diameter FWHM. This power is chosen as it fully activates the photoconductor without saturating it.

The LIDEP chamber is moved by an actuator in the x direction whilst the laser and camera are kept stationary. The particles are dragged along with the chamber unless they are trapped by the DEP force [see Fig. 1(b)]. Thus when particle tracking software [10] is used to analyse a video of the chamber being moved in the positive and then negative x direction at the same speed, two distinct positions for the particle can be seen [see Fig. 2(A)]. The drag force experienced by the trapped particle moving in the fluid can be described as follows;

$$F_{drag} = 6\pi r\eta v \quad (1.1)$$

Where r is the Stokes radius (here just the radius of the particle), η is viscosity and v the velocity. As the particle is close to the chamber wall we have to allow for Faxen's correction;

$$F_{drag} = \frac{6\pi r\eta v}{\left(1 - \frac{9}{16}\left(\frac{r}{h}\right) + \frac{1}{8}\left(\frac{r}{h}\right)^3 - \frac{45}{256}\left(\frac{r}{h}\right)^4 - \frac{1}{16}\left(\frac{r}{h}\right)^5\right)} \quad (1.2)$$

Where h is the distance from the surface to the center of the particle [8]. Thus as we move the LIDEP chamber faster, more force is exerted on the particle, which moves it further from the trap center. This ability to apply a varying force on the particle and measure its position is a simple but very powerful technique as it allows us measure the profile of the LIDEP trap, i.e. to plot the force that a particle will experience at different positions within the trap [see Fig. 2(B)].

3. Simulations

Simulations were carried out using the Finite Element method (COMSOL Multiphysics) which solves Maxwell's equations in the quasi-static approximation. This approximation simplifies the equations by assuming that the electromagnetic fields do not lag behind their sources but vary in phase with them. The quasi-static assumption can be justified if the

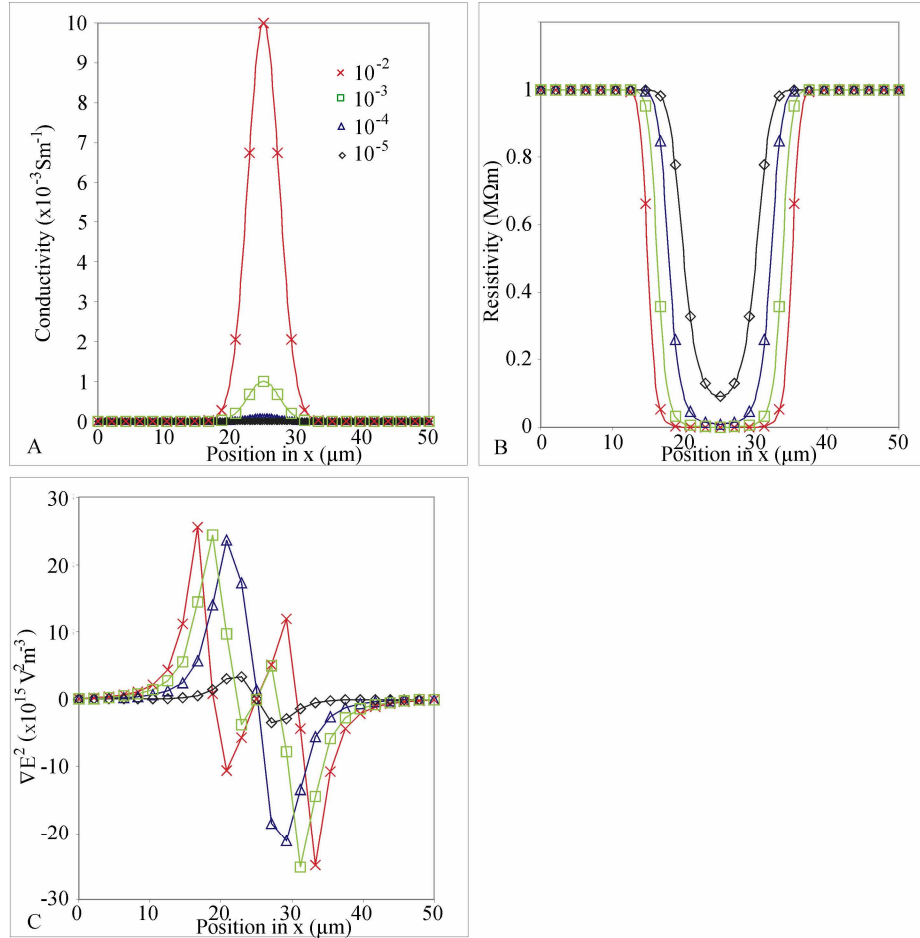


Fig. 4. (A). The illuminated conductivity is modelled as a Gaussian distribution with maximum conductivities 10^5 , 10^4 , 10^3 and 10^2 Sm^{-1} . (B). The resistivities this creates. (C). As the position of the peak gradient in the resistivity moves further from the center of the trap, so does the position of the peak force.

electromagnetic fields vary slowly. This is the case when the wavelength that corresponds to the frequency of the applied AC (here 2kHz) is large compared to the size of the LIDEP chamber. It also assumes that the coupling between the electric and magnetic fields can be ignored, which can be justified as the skin depth is large compared to the thickness of the layers the current passes through. Each layer of the LIDEP chamber is defined with the appropriate conductivity and permittivity assigned. The electrical response of the photoconductor to the laser beam is modelled as a Gaussian change in the conductivity of the a-Si [see Fig. 3(A)]. The force due to dielectrophoresis is given by;

$$F_{DEP} = 2\pi r^3 \epsilon_m \text{Re}[K(\omega)] \nabla E^2 \quad (1.3)$$

Where r is the radius of the particle, ϵ_m is the permittivity of the medium, $\text{Re}[K(\omega)]$ is the real part of the Clausius-Mossotti factor (see appendix) and ∇E^2 is the gradient of the square of the electrical field. Thus to find the DEP force we need to simulate ∇E^2 . Figure 3(B) shows ∇E^2 in the x direction for the case of a $5\mu\text{m}$ optical spot. The gradients are large and

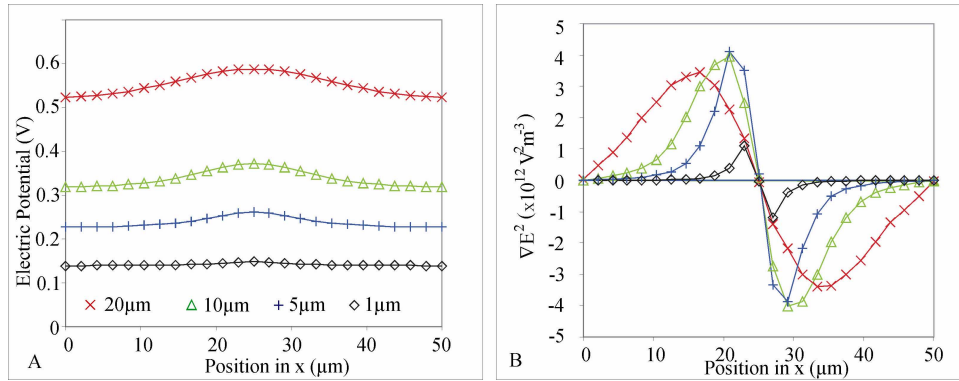


Fig. 5. Changing the optical spot size. A) The potential is plotted for case a 1, 5, 10 and 20 μm diameter optical spot and case B) The gradient of the square of the electrical field is plotted for the four spots.

positive on one side of the spot and large and negative on the other side, resulting in an effective trap for the particle. In the vertical direction, the force also decreases rapidly with distance from the a-Si surface. The simulated force on a 2 μm particle is calculated from Eq. (1.3) using the data for a position of 1 μm above the surface, i.e. using a single value for the whole of the particle; this will introduce a small error, as the actual force varies over the volume of the particle. The data is then compared to experimental data using a Clausius-Mossotti factor of 0.55 [see Fig. 2(B)]. The experimental and simulated data fit well showing that our assumptions are justified. A 4.9 μm (FWHM) optical spot creates a trap with peak forces that are $5.28 \pm 0.25\mu\text{m}$ apart, i.e. the trap size is essentially given by the size of the illuminating spot. This is, however, not a general result for any LIDEP system, as the trap size also depends on the conductivity of the a-Si. The a-Si used here has a dark conductivity of 10^{-6} Sm^{-1} and an illuminated conductivity of 10^{-5} Sm^{-1} . When the simulations are repeated for different conductivities, we find that the force scales as the illuminated conductivity, but the trap size also changes [see Fig. 4]. This highlights the inherent trade-off between trapping force and trap size in LIDEP that is controlled by the a-Si conductivity.

Intuitively, one would expect, as was also stated in [3], that the trap size is controlled exclusively by the FWHM of the illuminating Gaussian beam. However, as Fig. 4(B) highlights, the resistivity curves are wider for higher illuminated conductivity, i.e. there is a direct relationship between illumination power and trap size [Fig. 4(C)]. The peak forces representing the trap size are separated by $5.28 \pm 0.25\mu\text{m}$ for 10^{-5} Sm^{-1} , $8.4 \pm 0.25\mu\text{m}$ for 10^{-4} Sm^{-1} and $16.6 \pm 0.25\mu\text{m}$ for 10^{-2} Sm^{-1} , respectively. The optimum illuminated conductivity would be 10^{-4} in this case, as this offers almost as much force as the more conductive films whilst keeping the trap size small enough for single cell manipulation. The 10^{-5} conductivity would offer a smaller trap size, but also a much weaker trap strength. So if a smaller size trap is desired, it is not possible to increase the trapping force by increasing the illuminating intensity as could be done with an optical trap. High intensity will just saturate the photoconductor and result in a larger trap. Equally, using a smaller illuminating spot of the same intensity would simply result in a weaker trap, as can be seen from Fig. 5.

Let us now consider trapping power. It was shown previously that a LIDEP trap can be created with 100,000 times less intensity than required for optical trapping (OT) [2, 3]. This value was estimated from the minimum intensity necessary to produce a LIDEP trap, i.e. where the trap is at its weakest strength. In contrast, we believe that it is much more meaningful to operate at the point where the trap is strongest, i.e. where one would operate the trap in practice. We therefore used the highest intensity that does not saturate the

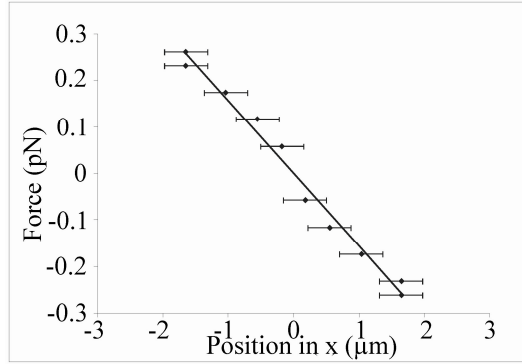


Fig. 6. The profile of a standard optical trap is measured in the same way as the LIDEP trap in Fig. 2(B) to allow for a direct comparison.

photoconductor. Furthermore, we quantify the strength of the trap via its stiffness, which yields the trap stiffness per mW of optical power as a useful figure of merit. For an optical trap, this figure of merit is independent of power and can be used to find the stiffest trap that can be created with a given laser power. We believe that this figure of merit is the most applicable for this comparison as ultimately it is the laser power available that limits the number of optical traps that can be generated of a given stiffness. For an accurate comparison between OT and LIDEP, we used the same optical setup and microsphere size, except for exchanging the laser pointer for a 1070nm fiber laser (IPG photonics) in order to give enough power for optical trapping. The optical spot in both cases is just below 5 μm and the particle size is 2 μm . The result is shown in Fig. 6. Using an optical power of 0.04 mW to operate the LIDEP trap near saturation of the photoconductor yields a trap strength of $1.49 \times 10^{-7} \text{ Nm}^{-1}$. For OT, a similar trap strength of $1.57 \times 10^{-7} \text{ Nm}^{-1}$ requires an optical power of 20 mW, so the stiffness per power ratio between the two methods can be determined as 470 ± 94 . This value is significantly lower than the 1×10^5 stated by [2]. The reason for this discrepancy is twofold; a) The illuminated conductivity of the a-Si is lower in our case than in [2]. As noted previously (Fig. 4), the force scales as the illuminated conductivity, hence our trapping force is lower. The benefit of choosing such a lower illuminated conductivity, however, is spatial resolution, which is higher in our case (note that the 1×10^5 value was determined for much larger traps); b) The LIDEP trap does not observe a linear relationship between power and trap stiffness due to the photoconductive process, e.g. we noticed that a 40-fold increase in power is required to increase the trap stiffness by a factor 5. Operating at the highest available trap strength therefore requires relatively more power than operating at the very minimum of trapping.

Overall, this discussion does confirm the advantage of LIDEP for creating traps on the micrometer scale with low optical powers, but it also highlights the practical limitations. Furthermore, OTs are usually created with high numerical aperture, e.g. 100x objectives. Using a high N.A. objective produces stiffer optical traps by decreasing the spot size, thus increasing the optical gradients for the same power. The same can not be done with LIDEP, as reducing the trap size decreases the electrical gradient produced as shown in Fig. 5(B).

4. Conclusion

We discuss the resolution limitation of an optical trap created by light induced dielectrophoresis (LIDEP) and show that a 5 μm optical spot can produce a 5 μm trap. We also show LIDEP trapping with positive (attractive) dielectrophoresis force, whereas most other demonstrations have relied on the negative (repulsive) force. Our key result is that trap size does not scale with the optical spot size, however, and we find that smaller spots can only be

created with the penalty of reduced trapping strength. While we have thus demonstrated LIDEP trapping of particles in the important size range of biological cells, we have also demonstrated an important limitation of the technique. Furthermore, the power required for trapping a particle using LIDEP compared to a gradient force trap is significantly (470 ± 94 times) stiffer per mW in our case, but this also depends on the electrical parameters used, especially on the ratio between illuminated and dark conductivity of the photoconductor. This clearly shows that the successful operation of a LIDEP device requires a good understanding of both its optical and its electrical properties.

Acknowledgments

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Appendix

The force due to dielectrophoresis is not only dependent on the gradient of the electrical field squared but also the Clausius-Mossotti factor [see Eq. (1.3)]. This factor depends on the complex permittivity of the particle and the medium, see Eq. (2.1) [9];

$$K(\omega) = \frac{\epsilon_p^* - \epsilon_m^*}{\epsilon_p^* + 2\epsilon_m^*} \quad (2.1)$$

Where ϵ_p^* and ϵ_m^* are the complex permittivities of the particle and medium, respectively and are given by Eq. (2.2) [9];

$$\epsilon^* = \epsilon - j \left(\frac{\sigma}{\omega} \right) \quad (2.2)$$

Where ϵ is the permittivity, σ is the conductivity, and ω is the angular frequency of the applied AC Voltage, which yields a frequency - dependent force. Here, we have used a frequency of 2kHz, which yields a positive DEP force. The conductivity of small particles is given by Eq. (2.3) [9];

$$\sigma = \sigma_{bulk} + \frac{2K_s}{r} \quad (2.3)$$

Where σ_{bulk} is the bulk conductivity of the particle material, for latex $1 \times 10^{-16} Sm^{-1}$, r is the radius of the particle and K_s is the surface conductivity. The conductivity of the particle is thus dominated by the surface conductivity and is inversely proportional to the particle's size. Therefore, different size particles exhibit a different Clausius-Mossotti factor, which allows the separation of different size particles via the LIDEP force.

Figure 2(B) assumes a Clausius-Mossotti factor of 0.55 as this gives good agreement between experimental and simulated results. Using formulas 2.1 to 2.3 we can show that this value is reasonable as it is the value that would be given for a $2\mu m$ latex sphere with a surface conductivity of $1.2 \times 10^{-8} Sm^{-1}$.