Optical tweezers technology overview

Gradient optical traps, also called optical tweezers, have emerged over the last 25 years as promising tools for manipulating microscopic dielectric objects with forces within the piconewton range. The power and extent of this technique are highlighted by the large variety of applications in diverse fields such as biology/biophysics, microfluidics, colloidal physics or liquid crystals.
Optical tweezers exploit the forces derived form the radiation pressure produced from a highly focused laser beam. High NA microscope objectives are used to tightly focus the laser to a diffraction limited spot so that a steep three dimensional light gradient is created in the immediate vicinity of the focus. The attractive force experienced by the trapped object is proportional to the light gradient and has to overcome the destabilizing effect of the scattering force. The first idea of a force gradient trap was reported by Arthur Ashkin in 1970, in 1986 he published the first experiments (Ashkin et al. Opt. Lett. 11 (5): 288–290). A typical optical tweezers setup uses one laser to create one or two traps. More complex optical tweezing operations performed with multiple optical traps can be achieved with integrated optics for beam steering, either by diffractively splitting the beam (dynamic holography) or by time-sharing of a single laser beam among several traps (acousto- or electro-optic deflectors).

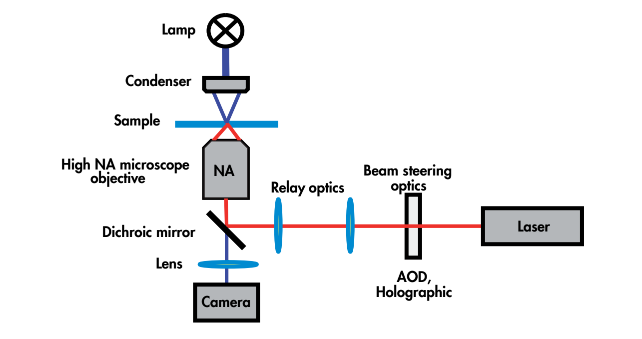

Fig. 1 Multi-trap laser tweezers setup

While the dynamic holography (holographic optical tweezers, HOT) offers the possibility of three dimensional manipulation of the trapped objects, the time sharing method has the advantage of the greatest flexibility, allowing for readily independent control of multiple traps.
In general the performance of any optical tweezer system can be characterised by the following parameters:

- Resolution and Accuracy
- Uniformity
- Linearity
- Speed

The recently launched optical tweezers system, Tweez250 (from Aresis, Ljubljana/Slovenia) integrates in a very compact design acousto-optic deflectors (AOD) that enable the creation and control of up to 2500 independent optical traps.

Resolution and Accuracy

We define the resolution of an optical tweezer, as the precision to which we can control the relative distance between two particles (Fig.2a). The accuracy is defined as how precise we can hold a trap in one position (Fig.2b)

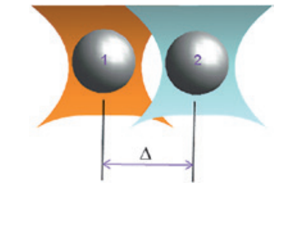

Fig. 2a Resolution

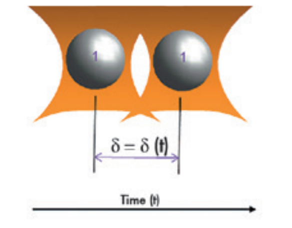

Fig. 2b Accuracy

The resolution of the system was determined with a dual trap experiment. One trap was fixed and the second one was moved sinusoidal with an amplitude of 100 nm and a frequency of 1 Hz (Fig.3 a). From this measurement the power spectrum of the mean square displacement between the two traps was calculated (Fig.3 b) resulting in a calculated resolution <0.001nm. For all practical considerations it is safe to specify a sub nm resolution for this setup.

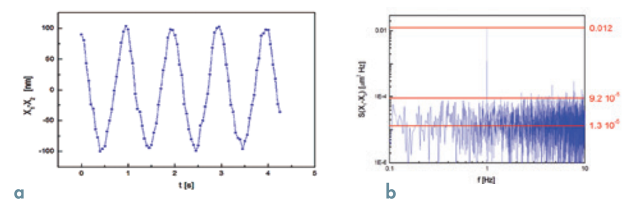

Fig. 3 Resolution of Tweez250 system

The same experiment was used to characterise the accuracy. The position of the two traps was recorded over time. The measured drift was in the range of 4nm/min (Fig.4 a). Their relative distance, however, remains stable with a value of <0.05nm (Fig.4 b)

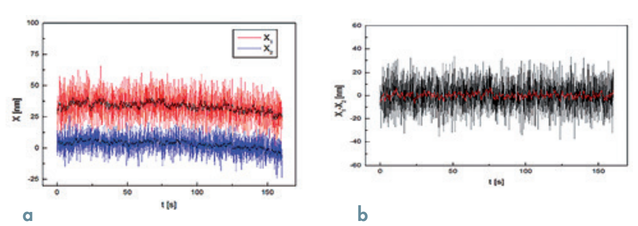

Fig. 4 Accuracy of Tweez250

Quantum Design
1 avenue de l'Atlantique
Bâtiment Fuji-Yama
91940 Les Ulis - France
Tél. : +33 1 69 19 49 49
france@qd-europe.com
www.qd-europe.com

Uniformity

One often encountered problem with tweezer systems is a non uniformity of trap intensity and therefore stiffness over the working area. This non uniformity can be as large as 30%. A specifically developed field flattening algorithm reduces the non uniformity to less than 1% over the entire working area of typical 150 x 150 µm^2. The exact working area will be dependent on the microscope objective.

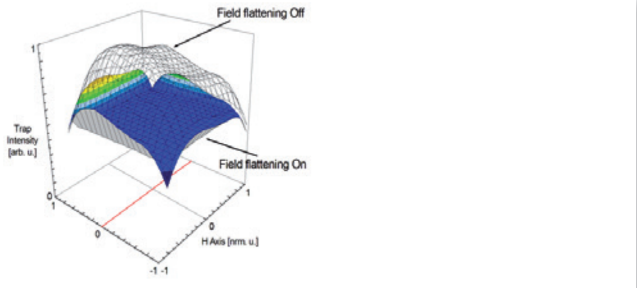

Fig. 5 Field Flattening algorithm to improve uniformity of trap intensity over working area

Linearity

The AOD amplitude response is not proportional to the radio frequency (RF) driving power. A linearisation algorithm minimises the deviation from linearity to <1%, see Fig. 6.

The combination of field flattening and AOD linearization results in a very stable and reproducible trap intensity or stiffness over a large working area and varying laser intensities

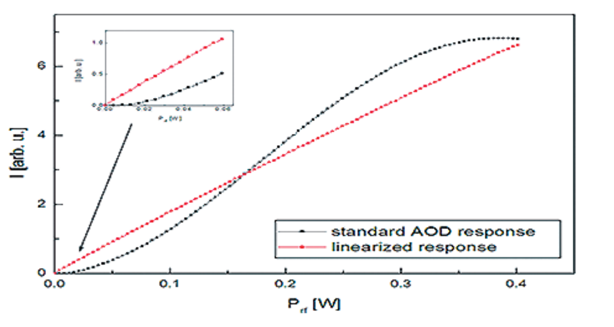

Fig. 6 Linearization of trap stiffness with respect to AOD RF driving power

Speed

As outlined earlier one of the major advantage using AODs for generation and control of multiple trap experiments is the possibility to operate an arbitrary number of traps in a time shared manner. The Tweez250 is software limited to 2500 traps. The switching rate between the traps can be as high as 100 kHz, a rate which is by far fast enough to ensure quasi-stationary condition for each trapped particle. One often encountered problem in time shared optical tweezer setups are the so-called ghost traps (Fig. 7 left). The intensity of these ghost traps can be as high as 25% of the original trap intensity. In the Aresis Tweez250 system ghost trap intensity is reduced to a value <1% of original intensity (Fig. 7 right) and therefore does not affect the experiment.

Fig. 7 Ghost traps in conventional time shared tweezer setup (left) and in the Tweez250 system (right)

Conclusion

There is strong evidence that optical tweezer systems are coming off age about 25 years after the first experiments have been published. Due to the small force ranges accessible with this technology new and fascinating experiments are possible in diverse fields like Life Science, Cell Biology, Colloidal Physics, Polymer Chemistry and others. This increasing interest makes it attractive for commercial suppliers to enter this field and replace the actually existing home built systems. Reproducibility and Ease-of-use of commercially available systems allows the researcher to focus on the experiment and not necessarily on the tweezer technology. The recently launched Tweez250 system from Aresis (Ljubljana/Slovenia) is an excellent example for this approach. It combines a high power 1060 nm laser with acousto-optic beam steering control in a very compact and stable design. It can generate up to 2500 independently accessible optical traps with an unmatched resolution and accuracy.

Quantum Design

Quantum Design
1 avenue de l'Atlantique
Bâtiment Fuji-Yama
91940 Les Ulis - France

Tél. : +33 1 69 19 49 49
france@qd-europe.com
www.qd-europe.com

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