Integrated monolithic optical manipulation†

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Received 11th April 2006, Accepted 3rd July 2006
First published as an Advance Article on the web 12th July 2006
DOI: 10.1039/b605237a

We present a new approach to optical manipulation that integrates microfluidic channels directly onto semiconductor laser material creating a compact integrated optical trap that requires no alignment and is wholly portable.

Introduction

Optical micromanipulation is now established as a powerful method for biological and colloidal science. It is a non-invasive method that is based on light scattering or refraction (without absorption) that may influence the motion of matter from the size of a single atom right up to the size of a large cell. Dual-beam traps,[1] single-beam tweezers[2] and complex optical landscapes[3] are used, but conventional systems all require discrete, macroscopic optical components to couple light from external laser sources into sample chambers. Our approach avoids the associated issues of size and alignment, creating a miniaturised system that is suitable for lab-on-a-chip applications. It addresses key challenges including that of incorporating lasers adjacent to a microfluidic flow, and it readily scales, offering the opportunity to conduct many complex scientific procedures in parallel, each with its own dedicated, pre-aligned lasers. The device's operation requires no end-user expertise; it may simply be placed on a platform with suitable electrical connections, and may be interfaced with a computer for automated operation. Observation, if desired, may be performed with any type of basic microscope system. Thus it will allow the non-invasive optical manipulation of biological specimens within a portable, self-contained lab-on-a-chip.

In this Communication we explain the device fabrication, and investigate the physical properties of the trap, whilst also demonstrating a variety of optical micromanipulation tasks. Particles are detected by monitoring the performance of the lasers, removing the need for an external microscope. Objects are released into a fluid flow and shunted between traps on this single monolithic block, paving the way for complex biological analysis chips where samples may be held, analysed and treated, and then guided to new interrogation regions, all by means of optical forces generated by the on-chip lasers.

Device design and fabrication

Our device is unique because the test chamber is built directly onto the semiconductor laser material. Therefore, the two main advantages of our system are its size and its intrinsic alignment. Firstly, each device contains multiple traps and yet is typically only 5 mm × 5 mm × 1 mm in size, taking up much less space than conventional systems, and allowing incorporation into portable testing devices. The electrical connections and plumbing add only slightly to the size. Secondly, every part is defined lithographically onto a single piece of semiconductor material, so no alignment is required, and there are no coupling losses; the laser beams enter directly into the test chamber where they interact with the specimen. This contrasts with conventional systems that use discrete, macroscopic optical components to couple laser beams from external sources into the sample chamber. A third advantage is that the lithographic design can incorporate virtually any planar configuration of traps, allowing complex systems to be built from these simple units, analogous to the use of transistors to build electronic circuits.

Our device is a counter-propagating beam trap configuration, which has recently seen a renaissance due to the simplicity of use, the low power density and large encatchment area, making it suitable for studies of cell abnormality[4] and optical binding.[5] It was introduced by Ashkin in 1970[1] and was realised using fibre optics by Constable *et al.* in 1992;[6] our optoelectronic trap represents a fully-integrated version of this geometry. The principle is the same for each incarnation: the gradient force draws particles onto the central axis between the beams, and the radiation pressure pushes them to the equilibrium point between the two independent beams.

Fig. 1 shows an illustration of a basic implementation. Particle flow in our system is initiated by either a guide laser or an external pump; a pair of two opposing lasers (A–B or C–D) may be switched on to hold a particle, and then off to release it. As described in more detail elsewhere,[7] the device is manufactured on a GaAs/AlGaAs heterostructure with InAs quantum dots that emit at 1290 nm. We have also used GaAs-based quantum well material to fabricate an analogous system that operates at 980 nm. Features are patterned *via* standard UV photolithography, and all etching is done using Chemically-Assisted Ion Beam Etching (CAIBE) with Ar : Cl_2 chemistry in our in-house machine. SU8-2000 photo-sensitive polymer provides electrical insulation, and metal contacts are applied in an electron beam evaporator (Edwards 360A). The final results of the fabrication are shown

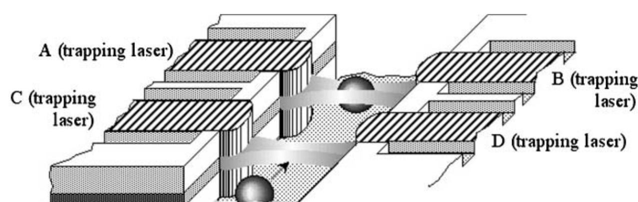

Fig. 1 Concept diagram showing basic implementation.

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† Electronic supplementary information (ESI) available: Motion of a polymer sphere within a dual-beam trap, and shunting between two traps. See DOI: 10.1039/b605237a

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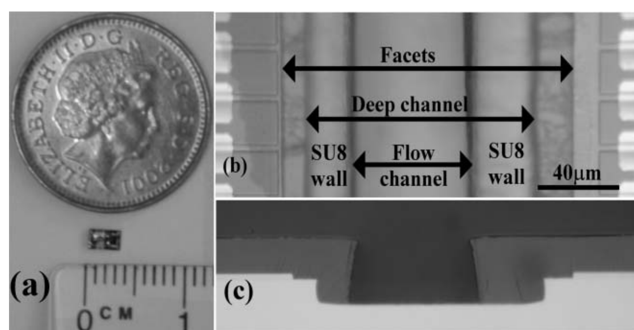

Fig. 2 (a) Size of prototype device next to a UK 1p piece; (b) plan view with channel running top to bottom; (c) cross-section through channel, in which SU8 on base is too thin to be seen.

in Fig. 2, which shows the size of a prototype device along with both a plan view and a cross-section of the trapping channel. The laser ridges are shallow etched (750 nm into the 1000 nm top cladding) to ensure single mode operation, with deeply etched (2 µm) facets to generate the required feedback. Quantum dot material was chosen because of the lower attainable threshold currents that minimise heating effects; operating at <5 V and <200 mA, each laser emits up to 20 mW (CW) of power into the channel, in a beam with high vertical and moderate horizontal divergence. The microfluidic channel is etched in between the two banks of facing lasers, and a coating of SU8 polymer prevents a short circuit. The power that enters the channel is deduced from the power that is emitted from the outer facets (not shown) at the edges of the device. Also not shown are the glass lid that seals the top of channel whilst allowing observation of the traps, and capillaries that connect the device to the external reservoir and pump.

Demonstrations

We demonstrate the ability of the lasers to perform a variety of useful tasks. As seen in Fig. 3, the trap can hold a range of biological and colloidal particles. Supporting on-line video footage† shows the trapping and motion of a 5 µm diameter polymer sphere, and also the shunting of this particle between two traps separated by 100 µm. This is accomplished by controlling the fluid flow to move the particle between traps where it is held and then released by switching the lasers on and off. Over short

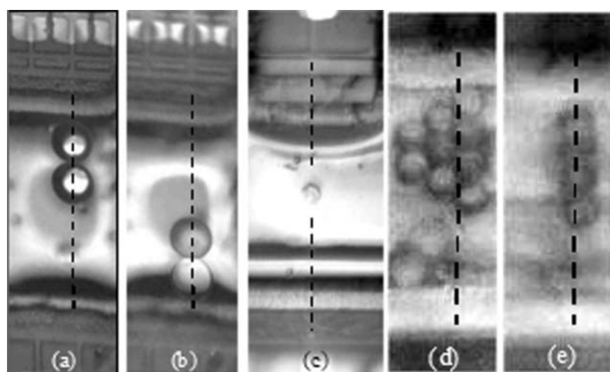

Fig. 3 Particles in a trap; channel runs left to right, and dashed lines show axes of beams: (a), (b) two 20 µm diameter polymer spheres pushed from one side to the other as relative beam powers are varied; (c) an SA2 cell; (d), (e) alignment of a crystal in the vertically divergent beams.

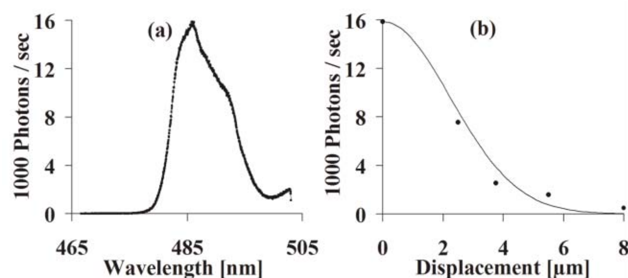

Fig. 4 (a) Fluorescence signal at trap centre; filters account for the sharp edge; (b) maxiumum signal (at 485 nm) as sphere is translated across the trap.

distances ($\sim$100 µm) the force from an integrated laser that is aligned along the channel can provide the propulsion.

Interrogation and spectroscopy of the trapped object is a key component of any analysis system: we perform fluorescence microscopy on the trapped object in the monolithic trap. The output of a violet laser diode operating at 411 nm is introduced *via* an external microscope into the centre of the channel, and excites fluorescence at 485 nm in trapped, dyed 5 µm diameter polymer spheres. Fig. 4(a) shows that the signal from inside the trap is clearly detected by a spectrometer. Varying the relative beam powers changes the trap equilibrium position and hence translates the trapped sphere away from the centre of the trap (Fig. 3(a), (b)); the intensity of the 485 nm peak falls, as seen in Fig. 4(b), by which the particle's position can be monitored. Detection is possible without an external microscope because the facing lasers affect one another, offering integrated methods of detecting and measuring particles. Each laser sends some light into the facing laser, increasing its output power, as measured from the outer facet; the presence of a particle in the beam inhibits this process, and so the output power gives an indication of the presence, and even the size, of the trapped particle. Alternatively, if the facing laser is reverse-biased then the incident laser light produces a photo-current whose magnitude is reduced by the presence of a particle, and which depends upon the size of the particle.[7] As an example of optical actuation we demonstrate, in Fig. 3, a large crystal structure moving from the horizontal plane to the vertical plane as it aligns itself with the highly-divergent beams, minimising its energy in the applied laser field.

Physical properties of the trap

The physical characteristics of the trap are also investigated. It should be noted that the large beam divergence from the diode lasers significantly reduces the optical intensities in the channel where trapping takes place. For this reason the values obtained are generally lower than those for focused optical tweezers.

The trapping efficiency (Q-value) quantifies the extent to which the incident photon momentum is transferred to the trapped object to give a resultant trapping force. For a given power we record the flow speed at which a trapped particle is ejected and use a simple relation between the Stokes drag and total input power of both beams to determine Q.[8] Table 1 shows data obtained for different polystyrene spheres and different facet separations. Clearly the Q-value increases with particle size because a larger cross-sectional area intercepts more of the available light. It also increases as the

Table 1 Table of transverse Q-values for different combinations of facet spacing and sphere diameter

Facet spacing/μm	Sphere diameter/μm 2.0	2.4	5.0
38 ± 1	0.0176 ± 0.0069		
74 ± 1	0.0046 ± 0.0022	0.0051 ± 0.0015	0.0303 ± 0.0148

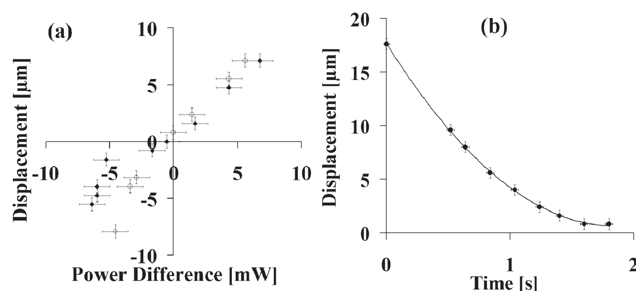

Fig. 5 (a) Displacement with power imbalance; (b) motion of a 2.4 μm diameter polymer sphere during restoration to the equilibrium position.

facet separation decreases, because the beams have diverged less and so are more intense.

The optical potential well is investigated by considering the variation of position with relative beam powers, which is seen in Fig. 5(a) to be roughly linear over a range of ~20 μm with a slope of ~1 μm mW^{-1}. The trap stiffness is deduced by monitoring the restoration of a particle to its equilibrium position after an initial displacement. Fig. 5(b) plots the relaxation of a 2.4 μm diameter polystyrene sphere back to the trap's centre when the lasers are set to 8 mW each. Following Constable *et al.*[6] the trap stiffness, expressed as a spring constant, k, is calculated to be $\sim 3.2 \times 10^{-8}$ N m^{-1}. This compares favourably with the values for fibre optical dual beam traps, but is, as expected, lower that those involved in molecular motor studies[9] that use optical tweezers.

These physical results show that our traps exhibit similar physical responses to conventional optical traps, and can be used to manipulate spheres, which are often used as 'handles' for biological matter. The manipulation of cells has been achieved, but the lower refractive index contrast between a cell and its surrounding medium gives much weaker forces.

Discussion and further work

There is much future potential for this integrated optical chip. The demonstrations that are presented in this Communication could be combined to create a device with more complex configurations of lasers and channels for the counting, interrogation and sorting of particles. Objects may be shunted around a large chip for multiplexed analysis, and switching between routes[10] could be accomplished by on-chip lasers. Those tests could be conducted *via* external apparatus,[11] or by monitoring the laser parameters, as discussed above. Such work can even be automated by creating a computer interface between the output signals and the lasers. The efficiency of the trapping and propulsion could be increased by shaping the facets to give focused beams or even more complex beam profiles.

The spectroscopy work could be expanded, using the signal variation in Fig. 4(b) as a feedback signal to position particles accurately, without the need for direct observations.[12] Once positioned, cells could be interrogated for Raman spectroscopy,[13] and subjected to photoporation[14] or other procedures. The need for an external fluorescence excitation source could be removed either by the use of tags that are pumped by the infra-red emission of the on-chip lasers, or by fabricating the devices in GaN-based material, allowing emission in the violet part of the spectrum and hence GFP (green fluorescent protein) expression.

The actuation of a microfluidic component demonstrated by the alignment in Fig. 3 could be refined to create a simple valve,[15] and other laser geometries could be designed to drive cogs[16] and pumps. As a final proposition, the device could have applications in the study of Bose–Einstein Condensates (BECs).[17,18] If the channel geometries and facet shapes were correctly fabricated then the available few mW of power at 1290 nm would be sufficient to create dipole traps for a BEC.

In conclusion we have realised a wholly integrated optical trap. The device manufacture uses established semiconductor processing techniques, giving a small system size and intrinsic alignment, and is cheap enough to allow disposable trapping devices when produced in volume. From a biologist's perspective, the system facilitates optical trapping in any microscope system without the need for specialised optics knowledge, and could greatly broaden the use of trapping in cell biology studies. By adding the powerful capabilities of optical trapping to the lab-on-a-chip toolkit, it could increase the use of combinations of trapping with other optical diagnostic techniques.

Acknowledgements

We thank the European Union fp6 NEST programme "ATOM_3D" and the UK Engineering and Physical Sciences Research Council for their support of this work. We thank Philip Jess for his assistance with the spectroscopic studies. Polymer spheres are from Duke Scientific.

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