OPTOFLUIDIC MANIPULATION WITH SUB-WAVELENGTH SCALE PHOTONICS

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ABSTRACT

Optofluidic transport represents the fusion of optics with microfluidics to create a new paradigm for nanoscale transport. Optofluidic transport exploits the favorable transport properties of light for the manipulation of objects in nanoscale systems. Here we demonstrate, for the first time, trapping and confinement of dielectric nanoparticles (75 and 100 nm polystyrene nanoparticle beads) using sub-wavelength scale planar photonic "slot waveguides". The slot waveguide generates previously unseen high confinement liquid-core optical modes, creating the necessary optical intensity for nanoparticle trapping. The ability to precisely manipulate nanoscopic matter is critical for the development of emerging active nanosystems.

KEYWORDS: Optofluidics, Optical Trapping, Waveguides, Nanofluidics

INTRODUCTION

Microfluidics can deliver samples to the general area of a sensor, but scales unfavorably as the cross sectional length scale decreases. We recently developed an alternative nanofluidic transport mechanism, "Optofluidic transport" [1], which uses optical forces in nanophotonic devices to confine and propulse particles or biomolecular species. Two advantages of this are: (1) favorable scaling laws, where smaller confinement increases optical intensity and (2) suppression of thermal diffusion, enabling biomolecular immobilization without the use of chemical tethering.

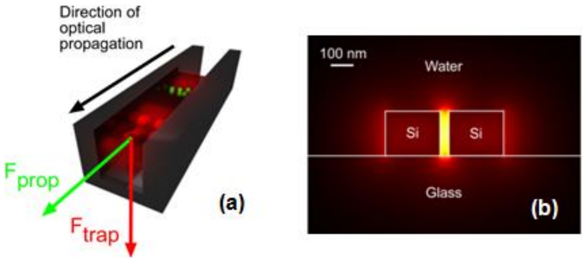

Figure 1. Slot Waveguide-Integrated Optofluidic Trapping Architecture (IOTA) (a) Schematic showing trapping of nanoparticles in exposed-mode slot region between two silicon waveguides. (b) Cross-sectional optical field distribution of slot waveguide submerged in water (n = 1.33).

THEORY

Illustrated in Figure 1, the slot waveguide [2] is comprised of a nanoscale (~100 nm) slot of low refractive index material, commonly air or water, sandwiched between two materials of drastically higher refractive index. Due to the high refractive index contrast in the slot region, there exists a pseudo transverse-electric (TE) mode

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which exhibits a large electric field discontinuity at the horizontal boundaries of the slot region. The combined effect of the small slot size with the large field discontinuities at the high/low index boundaries generates a high-intensity eigenmode in the slot, such that the majority of the optical energy is confined within the low-index region. Because of the high degree of confinement, a very strong field gradient over a distance less than 100 nm exists at the entrance region of the slot waveguide.

EXPERIMENTAL

The slot waveguide chips are fabricated using a electron beam lithography process. The total width of the waveguides is 450 nm with slot widths ranging from 80 nm to 160 nm. The slot waveguides are transitioned to nanotaper devices clad in silicon oxide to increase the coupling efficiency. The laser source is a tunable 1550 nm laser that runs to a tapered lensed fiber.

The particle solution comprises of suspended fluorescent polystyrene nanoparticles 75 nm and 100 nm in diameter (Duke Scientific) with refractive index n = 1.574 in a 100 mM phosphate buffer solution. The particles have about a 10% dispersity in particle diameter. 1% v/v Triton X-100 non-ionic surfactant is added to the particle solution to prevent aggregation of the nanoparticles and to limit adhesion of particles to the surface of the devices and PDMS microchannels.

The experiments conducted use devices that are bonded to a PDMS microchannel 100 um wide and 5 um tall. The fluidics are driven using an adjustable air-pressure system designed to maintain a constant pressure to the device. The power output of the fiber during the trapping experiments was set from 250 to 300 mW of power. Particle trapping was confirmed by counting immobilized particles and counting the number of released particles. Images of the experiments were captured at a rate of 55 ms per frame using a SensiCam CCD camera.

RESULTS AND DISCUSSION

As shown in Figure 2(a) we are able to trap the flowing nanoparticles in the slot waveguide device flowing at average speeds up to 80 μm/s and release them by removing the laser source or changing the polarization. For details on the experiment see the Methods Summary section. We observed increased trapping at slower particle flow speeds and at higher optical powers. We also observed radiation pressure propulsion of particles at average speeds of 1.5 μm/s, as shown in Figure 2(b). The relatively low speed transport of nanoparticles is due to the smaller particle sizes coupled with the use of a long wavelength light source. From Rayleigh theory we expect a λ^{-4} dependence of propulsion velocity on excitation wavelength, thus this speed could be dramatically increased by switching from Silicon waveguides to Silicon Nitride which is transparent at lower wavelengths.

While the majority of particles were observed to trap in the high-intensity well region of the waveguide, trapping was also observed in an off-center location, along the sides of the slot waveguide structure where a more traditional evanescent field exists. A particle experiences the strongest trapping forces at points where the electric field gradient is strongest, therefore, we would expect different behavior for the two different trapping positions [3].

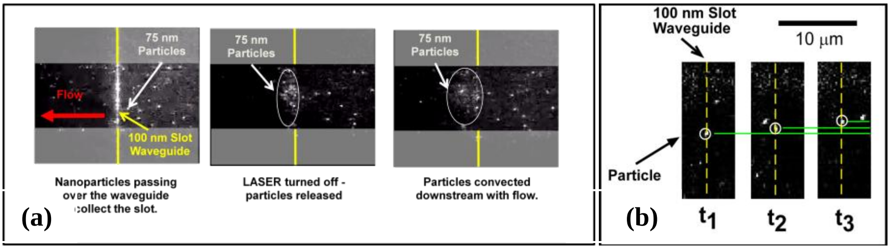

Figure 2. Still-frame captures of captured nanoparticle release and transport. (a) Waveguide is optically excited while 75 nm polystyrene nanoparticles are flowed in the overlaying microchannel over 100 nm slot waveguides. Over time, particles collect in the slot and also on the sides of the waveguide. At t=0, the laser source is removed and particles are released from the waveguide. Immediately after release, a 'cloud' of particles forms as the particles leave their trapping sites and the released particles are carried down the channel due to fluid flow. (b) Trapped 100 nm nanoparticles in 120 nm slot waveguides are transported a short distance by radiation pressure.

CONCLUSIONS

In conclusion, we have demonstrated the ability to trap nanoscale dielectric particles using a slot waveguide structure with high-intensity, fully accessible optical fields. Just as waveguide transport on the micrometer scale could be applied to biological cells, the slot waveguide could similarly be applied for biomolecular transport on the nanoscale.

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