Optofluidic Propulsion Using Nanophotonic Structures

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Abstract
The goal of this research is to develop a new class of micro-/nanofluidic device which exploits the intense electromagnetic fields present in micro- and nanophotonic structures as the primary transport mechanism. This mechanism exploits the near-field optical gradients (which serve to confine particles through a Lorenz force) and concentrated optical energy (resulting in intense scattering and absorption forces for propulsion through photon momentum transfer) present in these devices to perform a series of particle handling operations including transport, concentration and separation. We present our experimental results using waveguides fabricated from SU-8 cross-linked polymer integrated with polydimethylsiloxane (PDMS) microfluidics demonstrating the dynamic trapping of flowing particles and subsequent radiation pressure propulsion. Figure 1 shows a schematic of our system along with a mode field calculation illustrating the force vectors applied to the particle. These devices have the potential to develop into sophisticated optical train tracks, allowing for a new paradigm in particle manipulation.

Summary of Research
The ability to perform controlled trapping and concentration of nanoscale objects is becoming an important part of the development of high sensitivity, low limit of detection nano-sensor devices. Essential to the development of integrated microfluidic devices incorporating such functionality is the ability to fuse active target handling components with electrical and/or optical sensor elements. Traditional optical trapping mechanisms allow for a great deal of control in two dimensions, but exhibit a fundamental limitation. It is well known that electromagnetic forces applied to a particle are proportional to the intensity of the incident light. This intensity is equal to optical power divided by the cross sectional area (spot size) of the trapping laser. To achieve the necessary intensity for trapping smaller particles, smaller spot sizes obtained using high numerical aperture lenses are needed. This necessarily results in a decrease in the interaction length between the optical force field and the transported particle, limiting the distance over which it can travel.

Waveguide structures confine light within microscale structures through total internal reflection over extremely long distances. While the majority of the optical energy is confined within the solid core of a waveguide, there exists a near-field non-propagating component called the evanescent field. This field extends from the waveguide surface and exponentially decays into the surrounding medium over a distance of a few hundred nanometers. This rapid decay in optical intensity results in a strong trapping field. Such confinement also enables radiation pressure propulsion of particles along the length of a waveguide.
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Experimental Setup

Our experimental setup is illustrated in Figure 2. We use a syringe pump to flow our particle solution through the channels. The particles used are polystyrene beads of various diameters which are impregnated with green or red fluorescent dyes sensitive to specific wavelengths. Dichromatic filters and a mercury lamp provide the excitation light, and filter out unwanted wavelengths (excitation and laser). Our particle solution is made using a 100 mM 7.0 pH phosphate buffer solution in a 100:1 ratio with our particle suspension.

Experimental Results

We were able to achieve trapping of 3 µm polystyrene spheres on our waveguides with bulk particle speeds of up to 10 µm/s, and at an input laser power of 80 mW. Once trapped, particles exhibited propulsion due to radiation pressure, as seen in Figure 3. The image frames are explained as follows: (a) Position of particles pre-trapping, white line indicates (b) Top particle (red) reaches waveguide structure (c) Propulsion of red particle along waveguide structure. Blue particle nears waveguide (d) Red particle no longer trapped on waveguide. Propulsion of blue particle along waveguide (e) Continued propulsion of blue particle (f) Both particles no longer interact with waveguide.

The propulsion speed was considerably faster, almost double the bulk particle speed. This resulted in a considerable shift in particle position before and after trapping, even with the relatively short trapping time. The untrapping of particles in this particular case were due to collision with the sidewall of the microchannel (upper particle), and a minor defect in the waveguide (lower particle). As scattered light from the waveguide is filtered out during our experiments, we believe this effect may have been due to two-photon excitation, as our particles are excited at 542 nm, while the laser wavelength is at 980 nm.

Fabrication

The chosen waveguide material is SU-8 which is an excellent waveguide material with high transparency in the wavelength range of interest (850-1100 nm) for trapping applications. SU-8 is also compatible with many substrates, although for this experiment fused silica was used as the test substrate. The fused silica has a refractive index of 1.453, while the exposed SU-8 film has a measured refractive index of 1.554 at $\lambda = 975$ nm, which along with the water cladding with refractive index of 1.33 provides for significant refractive-index contrast for high confinement and strong evanescent field gradients. The waveguide dimensions were chosen to be a height of 560 nm and a width of 2.8 µm. An SEM of the SU-8 waveguide is shown in Figure 4.