Planar silicon microrings as wavelength-multiplexed optical traps for storing and sensing particles†

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Received 29th June 2011, Accepted 22nd September 2011
DOI: 10.1039/c1lc20574a

We demonstrate the trapping of particles with silicon microring resonators integrated with waveguides. Multiple microrings with different resonant wavelengths are integrated with each waveguide. We demonstrate that tuning the laser wavelength to the resonance wavelengths of different rings enables trapped particles to be transferred back and forth between the rings. We demonstrate that the change in output power arising from particle-induced resonance shift enables the real-time monitoring of trapped particles, such as their number and velocities, without the need for an external imaging system. The techniques we describe here could form the basis for small footprint systems in which objects are moved between multiple locations on a chip, at each of which different operations are performed and the objects’ properties sensed.

Introduction

The precise manipulation of micrometre size objects is advantageous for lab-on-a-chip devices, for applications such as the handling of single cells,† flow cytometry‡ and self-assembly.§ The transport of microparticles in microfluidic devices can be achieved using approaches such as pressure driven flow and traveling wave dielectrophoresis.§ However, using these traditional micromanipulation techniques, the manipulation of a single particle in a precisely controllable manner is difficult. Using optically-induced dielectrophoresis, Chiou et al. demonstrated the dynamic manipulations of microparticles down to the single particle level.¶ However, the requirement that the experiments be performed in low conductivity buffer, and the difficulty with which small particles are manipulated, limit its applications. Lee et al. also demonstrated a single cell manipulation technique based on magnetic forces.¶ This approach requires, however, for particles with a magnetic moment to be attached to the cell, meaning that, as the authors described, additional sample preparation steps are needed.

The use of optical forces to manipulate nanoparticles and biological materials has attracted attention recently due to its ability to operate on the single particle level, the possibility of reconfiguring the trapping potential, and its non-invasive nature. Integrated optical trapping using evanescent fields to trap small objects on the surfaces of photonic devices has been demonstrated for the manipulation of nanoparticles,†* molecules§ and live cells.¶ Integrated optical manipulation has several advantages over free space optical tweezers. In photonic devices, especially those based on surface plasmons,‖‖ optical fields can be confined to dimensions smaller than the free space diffraction limit, presenting the opportunity for trapping with improved spatial resolution. The use of photonic devices also offers the possibility for optical manipulation with multiple traps operating in parallel, in a system with a far smaller footprint than traditional optical tweezers based on microscopes. Using different photonic devices, a variety of manipulation functions have been demonstrated, including delivery,¶ trapping,¶¶ switching¶¶ and sensing.¶¶¶

Two problems, however, have obstructed integrated optical manipulation chips, in which the photonic tweezer structures are integrated with waveguides, from being adopted in a widespread fashion: (1) the ability to store a single particle at different locations on the chip, and to move it between these positions, has not, to the best of our knowledge, been demonstrated; (2) external imaging systems, usually fluorescent microscopes, have, to the best of our knowledge, been previously required to monitor the trapped objects. These imaging systems have large footprints and limited fields of view, limiting the possibilities for truly massively parallel processing.

We recently showed that sub-micrometre latex particles can be trapped and released by Si microrings.¶¶¶ This device enables particles to be stored. The integration of multiple microrings with different resonance wavelengths onto a waveguide presents the opportunity for trapping a single particle at different locations on a chip. The position at which the particle is trapped would be controlled by the input wavelength, and the particle would be transported between the microrings by the waveguide. We term such a device a “particle storage chain”. Here, we demonstrate two particle storage chain designs. Each consists of two microrings with different resonance frequencies. In the first
design, termed a one-way particle storage chain, two microrings, separated by several tens of μm, are integrated with a bus waveguide. By changing the wavelength of the laser input to the chip, particles can be switched from the first ring to the second, traveling between them on the waveguide. In the second design, the two microrings are located on opposite sides of the bus waveguide, about the same position along it. This enables trapped objects to be switched back and forth between the rings by modifying the laser wavelength. We term this device a two-way particle storage chain. In addition to the storage chains, we demonstrate that the output signal from the bus waveguide enables monitoring of the trapped objects without an external imaging system, since the presence of a particle on a ring modifies its resonance frequency. The same phenomenon has been used for detecting very small objects, but these demonstrations were performed with resonators coupled to with tapered optical fibers,20,21 in contrast to the approach we demonstrate in which the resonators are integrated with waveguides. We combine this high resolution sensing technique with our particle storage chains and demonstrate the counting of trapped particles, and the determination of particle velocity from the output power.

Experiments

Fig. 1 shows the schematic diagram of the one-way particle storage chain, comprising two microrings integrated with a waveguide. Microrings are fabricated in the top silicon layer (220 nm thick) of a silicon-on-insulator (SOI) wafer. The fabrication process begins with cleaving the SOI wafers into chips. Each chip is then coated with polymethylmethacrylate (PMMA) resist followed by a prebake at 180 °C for 10 min, and the patterns are exposed using electron beam lithography with an acceleration voltage of 100 kV (Elionix ELS-7000). After developing the chip using methyl isobutyl ketone (MIBK) for 90 s, the patterns are transferred to the top Si layer by dry etching using SF₆ and C₄F₆ gases. A PDMS chip containing microfluidic channels (50 μm high, 200 μm wide) is bonded to the chip containing the Si microrings, and chip is placed in an experimental set-up for optical manipulation demonstrations. The output of a tunable laser (HP8168, near λ = 1550 nm) is amplified by a high power C-band erbium-doped fiber amplifier (EDFA) and launched into the waveguide to excite TM modes. A lens-tipped optical fiber with a focal spot size of 3 μm is used to couple light into the waveguide with a coupling loss of approximately 10 dB. Fluorescent polystyrene particles with diameters of 1.1 μm are delivered to the trapping region through the microfluidic channel during the tests. A syringe is used to inject the particles into a tube connected to the microfluidic channel. When performing optical manipulation experiments, we minimize the flow rate, in order for the forces acting on the particles to be optical in nature, as opposed to fluid drag forces. The flow is minimized by stopping the syringe, though beads are still observed to fluctuate in position, at <20 μm/s. The output optical beam from the waveguide is focused onto a germanium photodetector to measure the transmitted power. A fluorescence microscope is used to monitor the trapping process. Fluorescence from the polystyrene particles is excited with a green laser (λ = 532 nm, P = 0.75 mW). The fluorescent emission is imaged by a microscope objective (Nikon, NA 0.55, 50X) onto a charge coupled device (CCD) camera, with a longpass filter used to suppress the green excitation laser.

We first demonstrate particle trapping with a single ring (radius 5 μm) with a guided power of 5 mW in the waveguide. Our previous work showed that this power was sufficient to propel particles along a straight waveguide.19 Our results here demonstrate the optical manipulation of particles with a relatively small guided optical power of 5 mW, at flow rates close to zero. Increasing the guided power would enable a deeper potential well to be obtained, and particle manipulation to be carried out at larger flow rates. The entry of particles from the waveguide to the microring and the release of the trapped particles to the waveguide are achieved by shifting the incident wavelength onto, and away from, the resonant frequency, respectively. This process is demonstrated in Supplemental Movie 1. This demonstration suggests that microrings can be used to store microparticles or biological materials such as cells. This motivates us to integrate several rings on a waveguide, as we describe below.

One-way particle storage chain

The one-way particle storage chain (Fig. 2a) consists of two microrings, with radii of 5 μm and 10μm, integrated with a bus waveguide. The microrings have widths of 500 nm. The bus waveguide has the same width (500 nm) as the microrings. The transmission spectrum in Fig. 2b shows resonances at 1557.9 nm and 1561.2 nm that correspond to the microrings with radii of 5, and 10 μm, respectively. The relatively low Q (~800) of the microrings has the favorable attribute of preventing trapping from being lost due to particle-induced resonance shift. The insets on the bottom of Fig. 2b are CCD images of the particle storage chain when the input laser is tuned to the resonance frequencies of the smaller (left image) and larger (right image) rings. It can be seen that particles are only trapped on the on-resonance ring. The trapped particles are indicated with white arrows, and the positions of the rings and waveguide are indicated by yellow lines. When the laser wavelength is tuned away from the center of the resonance peak, less power is coupled into the resonator, and the velocities of the trapped particles decrease. When the laser wavelength is shifted further from the resonant wavelength of the ring, the field intensity in the ring resonator becomes smaller than that in the waveguide. Particles that are in
This device, which we term a two-way particle storage chain, consists of microrings fabricated on opposite sides of the bus waveguide. The top (bottom) microring has a radius of 10.6 (10.7) μm. The gaps between bus waveguide and microrings are 100 nm.

Different from the one-way particle storage case, the two cavities can couple with each other to form hybrid modes, whose field distributions are sensitive to the wavelength. Fig. 3b shows the measured transmission spectrum. The broader peak at 1550 nm corresponds to the resonance mode with the majority of its field confined in the top microring. A hybrid mode with a sharp dip around 1554.4 nm can be seen. The field distributions of this hybrid mode are discussed in the Supplemental Material, with FDTD simulations showing that the field distribution changes dramatically as the laser wavelength is varied about the resonance. As the wavelength is tuned from 1554 nm to 1554.5 nm, the field intensity in the bottom microring becomes increasingly large compared to the top microring. Particles are preferentially trapped on the microring with the higher field intensity, which can be controlled by tuning the incident wavelength. This is demonstrated in Fig. 3c–e. In Fig. 3c, the laser wavelength is 1554 nm, and particles are trapped on the top microring only. In Fig. 3d, the laser wavelength is 1554.15 nm, and particles are trapped on both rings. Lastly, in Fig. 3e, the wavelength is 1554.5 nm, and particles are trapped only on the bottom ring. In Supplemental Movie 3, we demonstrate that we can switch a particle back and forth between the two microrings by tuning the laser wavelength between 1554.5 nm and 1554 nm. In the Movie, the particle circulates twice around the corresponding microring in each step of the trapping process. The particle is released to the bus waveguide by setting the wavelength to 1555.5 nm.

The one-way and two-way storage chains we demonstrate present the interesting possibility of a “micro production line”, where objects are transported between different locations on a microfluidic chip, at each of which modification or characterization is performed.

**Sensing trapped particles in real-time by monitoring the output signal**

The trapped particles introduce a resonance shift of the microrings, and the shift depends on the properties of the trapped particles, including their number, size, position and refractive index. For the polystyrene particles employed in our experiments, trapping induces resonance redshifts due to the particles having refractive indices higher than that of the surrounding water. Similarly, with a fixed laser wavelength, the transmitted signal intensity from the output waveguide should also change as particles are trapped, a phenomenon that can be used to obtain, in real time, information about trapped particles. We demonstrate two example applications of this phenomenon: counting particles and measuring their velocity. The experiments are performed with a microring with a radius of 5 μm. In Fig. 4a, the output power as a function of time is shown as particles are successively trapped. The guided power in the waveguide at time \( t = 0 \) is 5 mW, with the laser wavelength being set to the microring resonance (1545.1 nm). Each of the steps in transmitted power, at \( t = 11s, 20s \) and \( 30s \), results from an additional particle being trapped, as verified by observing the CCD image. By monitoring the intensity of the output signal, particles can be
counted as they are trapped, a useful function for applications in which we want to store particles on the microrings. Fig. 4b shows, in enlarged detail, the signal (transmitted power vs. time) occurring while a single particle is trapped on the ring. The circling motion of the particle on the ring gives rise to a periodic change of the output power. The intensity maxima occur when the particle is located in the coupling region near the bus waveguide. We believe that the attenuation of the field intensity along the ring is the main reason for the oscillation of the output power. Non-negligible radiation loss, which is partly responsible for the low quality factor of the cavity, reduces the intensity of the fields as they propagate around the ring. Therefore, the

Fig. 3 Two way particle storage chain. (a) SEM image. (b) Transmission spectrum. Microrings have radii of 10.6 and 10.7 μm. Dip at 1550.0 nm corresponds to mode with majority of field confined in top microring, and dip at 1554.4 nm corresponds to a hybrid mode. (c–e) CCD images of particles trapped on different microrings at different laser wavelengths, whose values are indicated in panel (b). Yellow lines depict the positions of microrings and bus waveguides. White arrows indicate the trapped particles.

Fig. 4 (a) Output power as a function of time as particles are trapped. (b) Output power as a function of time, shown in enlarged detail. A single particle is trapped on the microring. A particle velocity of 39.2 μm s⁻¹ is calculated from the period of the signal (0.8 s).
optical force reduces from a maximum at the coupling region to a minimum when the particle is located at a position on the microring just before it returns back to the coupling region. We carry out calculations of the force on the particle at different positions on the ring using the Maxwell stress tensor method based on field distributions determined from finite difference time domain (FDTD) simulations. These calculations show that the component of the force that pulls the particle to the ring is \( \sim 25\% \) smaller when the particle is at the position on the microring just before it returns to the coupling region, compared to when it is at the coupling region. It can be expected that this reduced force should lead to a larger gap between the particles and ring surface, thereby resulting in a smaller resonance shift and a larger output power. The velocity of the trapped particle can be calculated by: \( v = \frac{2\pi - r}{r} \), where \( r \) is the ring radius and \( \tau \) is the period of the optical power signal, equal to the particle circling period. The measured velocity is 39.2 \( \mu \text{m s}^{-1} \) for single particle trapping. Similarly, when two particles are trapped, a velocity of 34.8 \( \mu \text{m s}^{-1} \) is measured, which is smaller than that of single particle trapping. This can be understood as follows. When two particles are trapped, the larger resonance shift leads to lower field intensity in the microring.

A number of exciting applications exist for this work. One could trap particles using the first microring of the one-way storage chain, and determine properties such as size and/or refractive index by monitoring the output signal. Based on the results of this characterization, particles could either be released to the trapping medium, or released to the waveguide, where they would then be propelled to the next microring and trapped there. In addition, one could count particles as they are trapped by the microring. Once the desired number of particles is trapped, one could deliver the trapped particles to the next microring on the waveguide. Using the two-way particle storage chain, one could store and switch particles between the two microrings. The particle storage, transport and sensing capabilities we describe could provide a platform for sample isolation, particle sorting and solvent exchange.

In our demonstration, we have successfully trapped particles with diameters between 320 nm to 5.3 \( \mu \text{m} \). Increasing the incident power could further extend the size range, to both larger, e.g. small cells, and smaller particles, e.g. viruses and nanoparticles. Nanoparticles present interesting possibilities, since they can be coated with antibodies. Shifts in the micro-ring resonance wavelength might be a means for detecting molecular binding to these nanoparticles.

The results demonstrate that the long waveguide section before the micro-ring resonator serves as a particle collector, providing a large surface area to capture particles and deliver them to the micro-ring resonator. We anticipate that this effect could be taken advantage of further. Namely, the surface area could be increased by lengthening the waveguide by forming it in a serpentine geometry. Other methods for increasing the capture rate include increasing the guided power, and making the microfluidic channel shallower than its present height of 50 \( \mu \text{m} \).

The particle induced resonance shift provides information about trapped particles, including their size, position, and refractive index. Particle information can be gleaned from the power intensity signal. Another means for obtaining this could involve the use of a second fast tunable laser to precisely measure the resonance wavelength in situ. In this way, one could achieve a compact system for the manipulation and label-free sensing of cells, viruses, and nanoparticles.

Conclusions

In this paper, we experimentally demonstrate two switchable particle storage chains for on-chip particle trapping and sensing. With the ability to quantitatively store particles on a microring, deliver them from one location on the chip to another, and switch them between rings, the demonstrated particle storage chains could be used as building blocks in the construction of larger systems with additional functionalities. Particle counting and velocity measurement have been demonstrated by monitoring the output power intensity, without the need for an external imaging system. The planar nature of the microring resonators potentially enables on-chip integration with other lab-on-a-chip components, and permits all-optical control of micro-particle or bio-objects delivery, storage and routing.

Acknowledgements

This work was supported by the Harvard Nanoscale Science and Engineering Center (NSfC), which is supported by the National Science Foundation (NSf) under grant number NSF/PHY06–46094. Fabrication work was carried out at the Harvard Center for Nanoscale Systems, which is supported by the NSF.

Notes and references