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Spectrally reconfigurable integrated multi-spot particle trap

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Abstract

Optical manipulation of small particles in the form of trapping, pushing, or sorting has developed into a vast field with applications in the life sciences, biophysics, and atomic physics. Recently, there has been increasing effort toward integration of particle manipulation techniques with integrated photonic structures on self-contained optofluidic chips. Here, we use the wavelength dependence of multi-spot pattern formation in multimode interference (MMI) waveguides to create a new type of reconfigurable, integrated optical particle trap. Interfering lateral MMI modes create multiple trapping spots in an intersecting fluidic channel. The number of trapping spots can be dynamically controlled by altering the trapping wavelength. This novel, spectral reconfigurability is utilized to deterministically move single and multiple particles between different trapping locations along the channel. This fully integrated multi-particle trap can form the basis of high throughput biophotonic assays on a chip.

The manipulation of small objects is playing an increasing role in molecular biology, biophysics, and other areas of the life sciences [1–4]. Techniques based on optical forces are very attractive because they eliminate physical touching and the risk of damaging delicate objects. Due to the intrinsic scaling laws, optical traps such as laser tweezers or dual beam traps work best on micron-scale particles. This enables not only direct manipulation of cells [5], but also the investigation of nanoscale biological molecules when bound to inorganic microbeads [6,7]. In recent years, the emergence of microfluidics, optofluidics, and lab-on-chip technology has produced a surge of innovative approaches to controlling the movement of small particles on a chip using light [8]. Microparticles have been manipulated using a variety of waveguide structures including solid-core waveguides [9], 1D photonic crystal waveguides [10], microrings [11,12], slot waveguides [13], photonic crystal fibers [14–17], and liquid-core waveguides [18–20]. These structures have been used to push, trap, concentrate, and sort both single and multiple particles. It would be particularly desirable to create on-chip traps that can simultaneously control particles at different locations and be able to change the configuration of such a multi-particle trap at will.

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Here, we present a novel photonic approach to creating a dynamically reconfigurable, fully integrated, multi-particle trap. The main feature of this device is that the number and position of the trapping locations are not predetermined, but are set and altered with the wavelength of the trapping light source. We demonstrate optical trapping of different numbers of particles in a fluidic microchannel, along with an analysis of the trap parameters. We then show how temporal modulation of the trapping wavelength can be used to implement controlled movement and trapping of objects in single file through an optical interrogation region.

This novel principle is based on multi-mode interference (MMI) waveguides and illustrated in Fig. 1. An MMI is an integrated waveguide that supports a large number of lateral and/or transverse modes [21]. Since these modes have different wave vector components along the propagation direction, their superposition leads to unique interference patterns which results in the creation of well-defined spot patterns at different propagation distances. These image formation properties have been exploited in solid-state photonics to create switches and couplers [22,23]. More recently, MMIs have also been implemented in optofluidic devices, for example, as liquid-core MMIs for on-chip interferometers [24,25] and for single virus fluorescence detection [26]. They have also been used for optical particle manipulation, specifically for pushing particles along the surface of an MMI using the scattering force produced by the guided optical field [27,28]. However, a chip-scale optical particle trap using MMIs has not been demonstrated. More importantly, the fact that the underlying interference effect leads to a strong wavelength dependence of the MMI behavior has not been exploited to date. Specifically, the product of spot number N and wavelength λ is constant for given MMI dimensions (width w , length L) and materials (index n_c). This property allows us to create a new type of particle trap since we can place the fluid channel at a position along the MMI where multiple spots are created from an initial single-mode input. In Fig. 1 (left), the simulated intensity distribution along an MMI is shown, leading to five equidistant spots at the channel location. Each spot can then be used to trap particles at the opposing channel wall as illustrated. Moreover, the MMI allows us to tune the wavelength and create a different spot pattern as long as $N\lambda = \text{const}$. Figure 1 shows that if five spots are created at 876 nm, then six spots appear at 753 nm using the same device.

We implemented this principle on a fully integrated optofluidic chip as shown in Fig. 2(a). A micron-scale channel (blue, cross section $5 \times 12 \mu\text{m}$) is terminated by two reservoirs from which particles can be introduced by pressure or an applied voltage. The channel is intersected by the wide MMI waveguide and a narrow, single-mode control waveguide. Additional solid-core waveguides to the left and right of the liquid channel can be used for collection of fluorescence or scattering signals. The near-IR optical trapping beams in this Letter are from a tunable Ti:sapphire laser (750–880 nm, Del Mar Trestles) that was coupled into a single-mode fiber (SMF, Newport Corporation) for a nominal output power of ~ 120 mW. The SMF was then butt coupled to a solid-core waveguide on the chip. Fluorescence and videos of particle manipulation were collected with a $50\times$ objective lens, filtered (Edmund Optics, 800 nm long pass) and detected by an overhead camera (Andor Luca).

The device was fabricated on a silicon wafer using dielectric layer deposition and sacrificial core etching to define the waveguides and fluidic channel, respectively. The MMI waveguide

consists of a 2.64 μm thick SiO_2 ridge on top of a $\text{Ta}_2\text{O}_5/\text{SiO}_2$ multilayer stack that forms an antiresonant reflecting optical (ARROW) waveguide on top of the Si substrate [29]. The optofluidic chip used in this Letter was fabricated on a 100 mm silicon substrate. The cladding layers below the hollow core on this chip consist of Ta_2O_5 and SiO_2 (refractive index: 1.47 and 2.107; thicknesses in nm starting from the substrate 265/102/265/102/265/102–5,000–5,820, where the material sequence reads $\text{SiO}_2/\text{Ta}_2\text{O}_5/\text{SiO}_2/\text{Ta}_2\text{O}_5/\text{SiO}_2/\text{Ta}_2\text{O}_5\text{-core-SiO}_2$) to ensure minimized background levels [28]. SU8 photoresist (SU8-10, MicroChem) was spun on the wafer, patterned, and developed to define the sacrificial material for the hollow fluid channel with a rectangular cross section of 12 μm wide by 5 μm high. A pedestal was defined by dry etching in an inductively coupled plasma-reactive ion etcher using the SU8 and a thin nickel layer as the mask. Then, a single SiO_2 overcoat layer of 5.8 μm thickness was deposited by plasma-enhanced chemical vapor deposition. The single-mode coupling and MMI waveguides of 4 and 75 μm width, respectively, were defined by another lithography and etch step. The inlet and outlet were exposed with a buffered HF wet etch through the top SiO_2 layer; then the SU8 was removed with a $\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2$ solution to form the hollow core. After surface processing, the chip was cleaved into a die, and the cleaved edges served as interfaces for waveguide coupling.

The $w = 75 \mu\text{m}$ wide ridge supports multiple lateral modes that create the desired interference patterns for a length of $L = 1.9 \text{ mm}$. The device was then tested for multi-spot formation. To this end, the channel was filled with fluorescent dye in an aqueous solution (100 μM , DyLight 830-B2), and low-power light from a tunable Ti:sapphire laser (Trestles, Del Mar) was butt coupled with a single-mode fiber into the narrow single-mode waveguide input of the MMI at the edge of the chip [see Fig. 2(b)]. The fluorescence patterns generated by the dye were recorded with a camera (Andor Luca S) from the top of the chip and are shown for two wavelengths in Figs. 3(a) and 3(b) [top]. Five and six spots at the design wavelengths of 876 and 753 nm are clearly visible. Note that the spots remain well defined along the propagation directions over longer distances than the 12 μm channel, so that we observe stripes with uniform lateral width. The bottom graphs of Fig. 3 show the intensity profile along the center of the channel. The experimental traces (symbols) match very well with the computed profiles (dashed lines) for both wavelengths. The 876 nm profile contains a weak background profile that is largest at the MMI center. This is due to weak reflections from the far side channel wall being in excellent agreement with the simulations. Well-defined spot patterns were observed up to 11 spots at 400 nm. Due to the laser's rapid and automated tunability between 753 and 876 nm, we focus on these wavelengths for the remainder of this Letter.

MMI-controlled optical trapping of multiple particles is demonstrated in Fig. 4. Inorganic microbeads ($d = 3 \mu\text{m}$, Invitrogen Sulfate Latex) in an aqueous solution were transported to the trapping region via flow induced by hydrodynamic pressure difference between the reservoirs. Flow speeds were kept below 2 $\mu\text{m/s}$ for all experiments, well within the range over which the optical force dominates and particles can be removed from the stream [20]. The particle concentration ($5 \times 10^7/\text{ml}$) was low enough to ensure single particle delivery to the trapping region and minimize channel clogging. Figures 4(a) and 4(b) show particles trapped at five and six well-defined locations, respectively, as defined by the MMI pattern. Figure 4(c) shows the particle trajectory of the leftmost bead (five-spot configuration) during

trapping from which the trapping potential landscape can be derived [18,30]. One example is shown in Fig. 4(d). The potentials exhibit an average depth of 10 kT for an estimated power of 18 mW per trapping spot at 876 nm and 7 kT for 22 mW at 753 nm. This shows that different multi-particle traps can be defined in the fluidic channel. Once trapped, particles are available for optical analysis, similar to the single spot optofluidic traps reported elsewhere [15–17]. We note that simultaneous application of two or more trapping wavelengths results in the generation of a large number of trapping locations while maintaining lower optical powers for the individual laser sources.

The spectral reconfigurability of the integrated trap enables additional, novel particle manipulation capabilities. Here, we demonstrate the delivery and transport of particles to and through the trapping locations in a controlled manner. Such capabilities have recently received significant interest due to the potential applications for particle sorting [31], cell and DNA analysis [11,32,33], and optofluidically integrated solutions [34–36]. Figure 5(a) illustrates this concept for a single microbead (see also “Visualization 1 “ for the complete sequence) that is originally held in the leftmost spot (#1) of the six-spot trap. When the laser wavelength is switched to 876 nm, the trapping locations are redefined to the five-spot locations. A weak additional flow from left to right nudges the particle into spot #1 of the five-spot trap ($t = 20$ s). When the wavelength is switched again, the bead is once again released and drifts to the right where it is trapped in spot #2 of the six-spot trap ($t = 33$ s). Successive wavelength switching sequentially moves the particle into each of the trapping locations where it can be held as desired. In this way, loading and controlled placement of particles in the trap can be accomplished entirely by dynamic spectral reconfiguration. Figure 5(b) and “Visualization 2“ illustrate how this concept can be used with the trap fully loaded with particles at each spot. The still frames in Fig. 5(b) show specifically how a new particle enters into the six-spot configuration and how the rightmost particle is expelled upon switching to five spots. Returning to the six-spot configuration redistributes the beads into the six available traps.

In summary, we have introduced a novel photonic technique for creating reconfigurable multi-spot particle traps on an optofluidic chip. An MMI waveguide intersecting a fluidic channel creates different numbers of trapping locations at well-defined wavelengths, allowing for particle manipulation with increased throughput as multiple particles can be held and analyzed simultaneously in a one-dimensional array. The technique can be scaled up by using multiple MMIs and fluidic channels on the same chip. Moreover, this approach can be combined with other functional elements of ARROW-based optofluidic platforms such as liquid-core waveguide fluorescence sensing [37,38], hybrid integration with a microfluidic sample preparation layer [38–40], and nanopore-gated electrically controlled delivery of single particles into the fluidic channel [41]. The MMI-based trapping principle is not limited to ARROWs as long as low-loss light propagation in the input single-mode and MMI sections is ensured. Therefore, this reconfigurable trapping concept can find numerous applications in fluorescence biosensing and analysis as optofluidic integration and on-chip particle manipulation continue to develop.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1. Schematic view of MMI interferometer waveguide with propagating light field at different wavelengths producing a different number of trapping beams in the intersecting fluidic channel.

Fig. 2.

(a) Schematic view of complete optofluidic chip showing waveguide layout and introduction of particles via attached reservoirs (total size $\sim 1 \text{ cm} \times 1 \text{ cm}$). (b) Scanning electron micrograph (SEM) of central region of chip in which the MMI waveguide is intersected by a $12 \text{ }\mu\text{m}$ wide fluid channel.

Fig. 3.

Fluorescence from quantum dots inside a liquid microchannel reveals generation of well-defined, equidistant excitation beams for on-chip optical trapping (top row). Line scans of the fluorescence intensity along the channel center show the spot profile (symbols) which match well with the predicted intensity patterns (dashed lines) [bottom row]. The number of spots depends on the wavelength; here (a) five at $\lambda = 876$ nm and (b) six at $\lambda = 753$ nm. (False coloring of the detected channel fluorescence visualizes the spectral tunability of the trap.)

Fig. 4.

(a) Still frame of five microbeads trapped in microchannel using an MMI-generated multi-spot pattern at $\lambda = 876$ nm. Also shown is the recorded trajectory of trapped bead #1 and the resulting trapping potential calculated from the trajectory statistics at this trapping point. (b) Still frame and trap analysis of six beads trapped simultaneously in six locations at $\lambda = 753$ nm. (c) Trajectory of leftmost bead during trapping, reflecting the confinement range along x and y. (d) Trapping potential profile extracted from trajectory in (c).

Fig. 5.

(a) Still frames of trapped bead in microchannel at different times. The trapping beam wavelength is alternated between 753 and 876 nm, resulting in a temporal variation of the trapping spot number and location. In combination with a weak lateral flow (speed 1.2 $\mu\text{m/s}$), the bead is deterministically moved and held through the channel (see Visualization 1). (b) Optical manipulation of multiple particles. Two still frames of trap loaded with six beads. Under repeated spectral switching as described in (a), the chain of beads is moved along the channel, with a new one entering from the left (left image) and the last particle being expelled from the trap during the five-spot half-cycle (right image) [see Visualization 2].