Sorting of polystyrene microspheres using a Y-branched optical waveguide

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Abstract: We demonstrate how a Y-branched optical waveguide can be used for microparticle sorting. Polystyrene microparticles, optically guided in the waveguide's evanescent field, are directed down the desired, more strongly illuminated, output branch. The output of a fibre laser at a wavelength of 1066 nm is coupled to the waveguide by direct butting. The power distribution between the two output branches is selected by the relative position of the fibre to the waveguide input facet. This provides a simple method for reliable particle sorting with very high probability of success under appropriate conditions. The method can be easily combined with other particle manipulation techniques of interest for micro total analysis systems of the future.

OCIS codes: (130.3120) Integrated optics devices; (140.7010) Trapping; (170.4520) Optical confinement and manipulation; (230.7380) Waveguides, channeled

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1. Introduction

Biological and chemical assays and analytical methods may be substantially improved by miniaturization of various components and their subsequent combining into systems. A particular advantage of microfluidic systems results from the ability to work with small sample sizes, within a closed and possibly complete analytical system [1]. Research on so-called Micro Total Analysis Systems (μTAS) or Lab-on-a-Chip, started in the early 90s and has attracted a great interest in the scientific community [2, 3]. One important functional module of μTAS is particle trapping and sorting. Several different techniques have been employed to achieve this, each with its own qualities and drawbacks. Mechanical trapping and sorting [4] on a microchip poses challenges because of the complex physical properties of biological cells. Electrical trapping and sorting may employ two different phenomena depending on the particle nature [4]. A DC field is applied for electrophoresis of charged particles. However, electrophoretic mobilities, being similar in nature for most biological particles, limit application of electrophoresis almost exclusively to pumping fluid through microchannels (electro-osmotic flow). On the other hand, a non-uniform AC field is used for dielectrophoresis (DEP) of polarizable (charged or neutral) particles. DEP has been successfully applied on microchip scales to manipulate and separate a variety of particles [4]. Although the electrical devices work well for fixed conditions, the voltages have to be finely tuned whenever conditions are changed [5]. Making more complex devices with more than one switching junction becomes problematic because of the need to compensate for the various pressure and resistive imbalances in the devices. Besides, poorly conductive media should be employed for DEP [6] which conflicts with the need for highly conductive media as a better physiological environment for living cells. Pressure-driven fluid flow (also called hydrodynamic flow) has also been proposed for liquid handling in microsystems [3, 7]. The key advantage of this method is its effectiveness for a wide range of solvent compositions and for channels made of a wide range of materials. However, a pump or a vacuum source is needed to provide large pressure gradients to drive fluid flow in small microchannels [7]. Recently, optical methods have been proposed to control microfluidic processes and achieve particle sorting. A multiple-beam trapping system has been proposed for powering active microfluidic components produced either by microfabrication or by colloidal formation [8]. Using a dynamically reconfigurable optical lattice MacDonald *et. al* demonstrated an optical sorter for microscopic particles [9]. In this paper, we present a new approach to sorting of microscopic particles using an evanescent field in the cover region of a y-branched channel waveguide. Optical manipulation of particles in the evanescent field of a prism was first experimentally demonstrated in the early 90s [10]. This was followed by the first demonstra-

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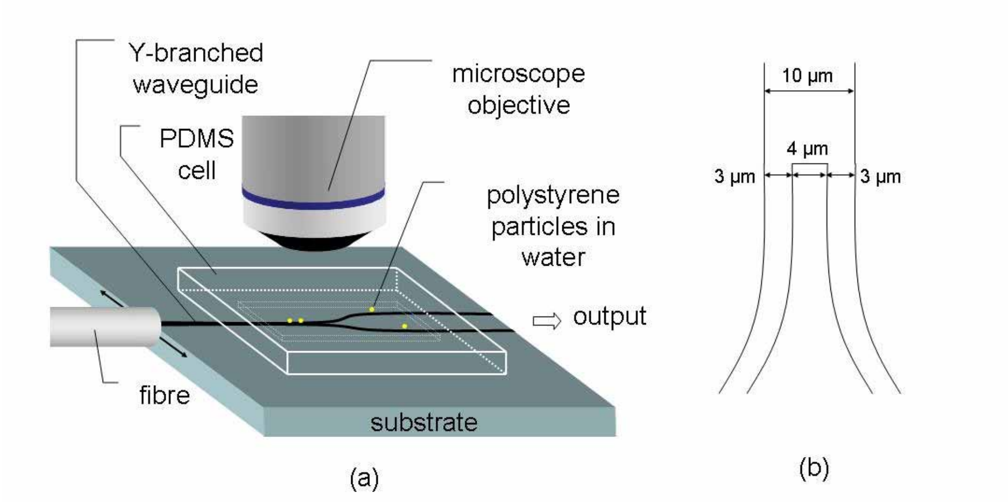

Fig. 1. (a) Experimental setup used for particle sorting. (b) Diagram of the waveguide junction region.

tion of particle guiding along an optical waveguide in 1996 [11]. Subsequently, experimental investigation of particle propulsion has been reported for dielectric microparticles and metallic nanoparticles on top of single-mode and multimode channel waveguides [12, 13, 14]. Recently, we have characterized optical propulsion of microspheres along a channel waveguide produced by Cs^+ ion-exchange in glass [15]. Here we employ similar waveguides, but with Y-junction branches, to manipulate particles further and demonstrate separation. We show how microspheres can be efficiently sorted down the two waveguide branches by changing the field distribution in the multimode input trunk. The extension of this method to biological particles requires the particles to be big enough and have sufficiently high refractive index relative to the surrounding medium. Alternatively, small biological molecules could be attached to latex spheres and thus manipulated by the optical field [15]. However, the intensity should be kept low enough to prevent the particles from being damaged.

In the next section we describe the experimental procedures. The results are presented and discussed in Section 3, which is followed by our conclusions.

2. Experimental procedures

The experimental apparatus used for particle sorting is shown in Fig. 1. Y-branched channel waveguides, about 4 cm long, were formed in soda lime glass by Cs^+ ion-exchange. The substrate was coated with an aluminium mask which was photolithographically patterned with Y-branched stripe openings. The input trunk was 10 μm wide. The output branches were 3 μm wide starting out with 4 μm gap between them in the junction region. Finally, they were brought to a separation of 200 μm with a branch bend radius of 8 mm. Ion-exchange was performed in molten $CsNO_3$ salt at $450^\circ C$. A diffusion duration of 10h resulted in a multi mode input branch and single mode output branches at 1066 nm, which is the wavelength of the fibre-coupled laser (IPG Photonics) used as the light source in our experiments. The light was coupled from the fibre to the waveguide by direct butting. The laser light was linearly polarized and the polarization set to TM with a rotational fibre holder. The fibre holder was mounted on top of a motorized linear stage which could be manipulated with submicrometer precision (Newport PM500). In this way the fibre position relative to the waveguide input facet could be precisely controlled

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thereby changing the field distribution within the Y-branched waveguide and hence the power travelling in each output branch. We used this simple mechanical technique in our experiment aiming for a proof of principle. Ultimately, it could be replaced by other methods such as integrated electro-optic switching or wavelength-dependent routing which could be employed in future on-chip systems. We manipulated polystyrene microspheres of 6 μm diameter (Duke Scientific), whose refractive index was $n = 1.59$ and specific gravity was 1.05 g/cm^3. Particles were diluted in de-ionized water ($n = 1.33$) at a concentration low enough to avoid formation of long particle chains [15]. The particle solution was confined on top of the waveguide in a closed cell (15x10x0.2 mm) formed in moulded polydimethylsiloxane (PDMS) elastomer. An optical microscope with a X10 microscope objective lens was used to observe the particles with bright field illumination from above. A filter was used to suppress the scattered laser light from the microscope image. A cooled CCD camera was mounted on top of the microscope and the images were recorded on a computer.

3. Results

In this section we show how Y-branched waveguides can be used to reliably manipulate polystyrene microspheres. Microspheres were evenly distributed over the substrate surface within the cell, and those within the waveguide modal evanescent field were optically trapped, and guided in the direction of power flow. Microspheres initially outside the modal field travelled under the influence of minor fluidic currents due to thermal gradients until they encountered the evanescent field and became guided. For fibre output power of about 165 mW, particles in the input trunk of the waveguide, about 100 μm from the junction, were guided at a velocity of 2.1 μm/s. Changing the fibre position relative to the waveguide input facet changes the field distribution at the junction and dictates how the power is distributed between the two output waveguide branches. The output power of each branch as a function of the fibre position relative to the waveguide input facet is shown in Fig. 2. In the case of an ideally symmetrical system, the relative heights of the two peaks would be expected to be the same. The difference in the peak heights could be accounted for by any asymmetry obtained in the fabrication process. The branches are referred to as the upper branch and the lower branch with respect to their orientation in the movie in Fig. 5. Adjusting the input fibre position clearly allows selection of the relative power in the two output branches.

In the first particle separation experiment we set the fibre position so that the power was initially equally distributed between the two branches, at a zero relative fibre position in Fig. 2. The fibre coupling was then left to drift as a result of unavoidable vibrations, air flow etc., while recording the temporal evolution of the output powers of both branches and simultaneous CCD camera images of the microspheres in the junction region. Whether a microsphere travelled into the upper or lower branch could then be correlated with the power in each branch at that time. A graph summarising the results is given in Fig. 3.

As each particle passed the junction region, we extracted whether it went into the upper or lower branch from the CCD images. In Fig. 3 each diamond corresponds to a particle which passed into the lower branch and each square corresponds to a particle which passed into the upper branch. These points are plotted against the output powers of the waveguide branches at the moment when that particle was in the junction region. It can be seen that in the majority of cases particles follow the branch that is illuminated with the higher power. The greater the difference in the output power of the two branches, the more likely it is that the particle will go down the more strongly illuminated one.

In the second separation experiment we aimed to send a specific particle down the desired waveguide branch by illuminating that branch with higher power. To allow switching of particles to one branch or the other, two fibre positions were chosen and the fibre was flipped

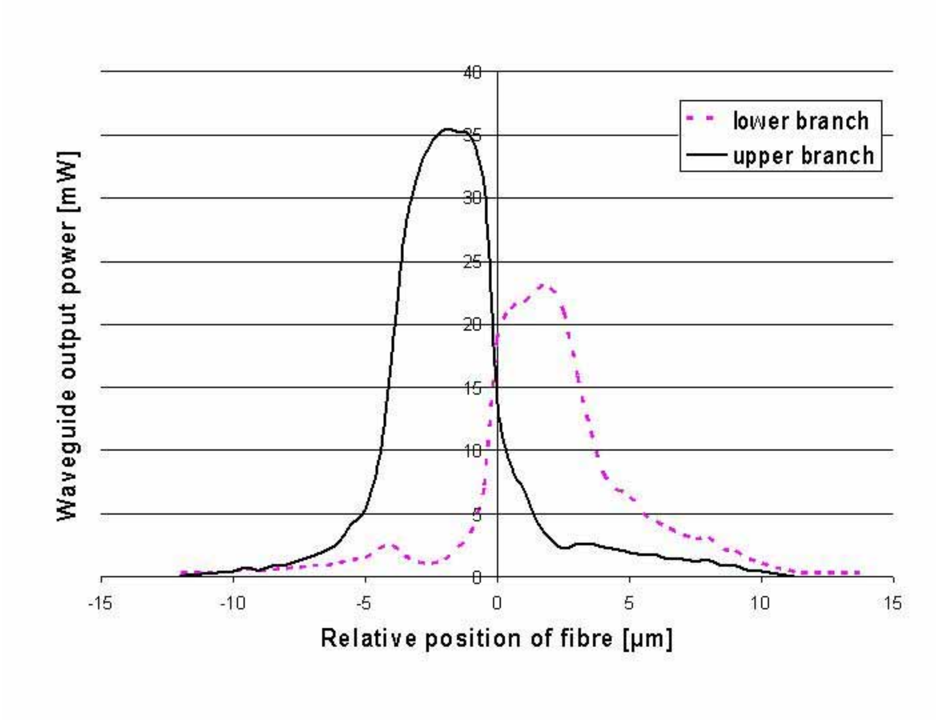

Fig. 2. Output powers of the upper and lower branches of the Y-branched waveguide as a function of the fibre position relative to the waveguide input facet. Fibre output power was about 165 mW.

between them. The positions were chosen such that the output power in the chosen branch was about 2 to 3 times greater than in the other branch. We found that this was an optimal power distribution, compromising between two demands. Firstly, the difference in the modal powers in the two branches had to be high enough for the particle to be propelled down the desired branch. Secondly, the power in the more weakly illuminated branch should be high enough for the particles already guided in it to remain trapped and propelled. Fig. 4 shows how the output power of both branches changed as the fibre was flipped between the two chosen positions.

The movie in Fig. 5 shows a CCD image of the junction region in which the polystyrene microspheres are sorted into one branch or the other at will with control by a simple ”mouse-click”. It was determined that two consecutive particles as close as 50 μm apart could be reliably separated by appropriately timed switching the fibre position. This minimum separation was set by two conditions. Firstly, a particle had to be about 40 μm away from the junction when the switching occurred in order to be sent down the desired branch with a high certainty. Secondly, a particle had to be at least 10 μm into the desired branch to ensure that it would stay there once the power was switched.

In our experiments the particle solution occupied the whole waveguide region, which allowed some of the particles to become trapped in one of the output branches after the junction, without previously being sorted. In a complete sorting system this would be prevented, perhaps by injecting particles a couple of hundred micrometers before the junction, by injecting them directly on top of the waveguide or by using a physical obstacle.

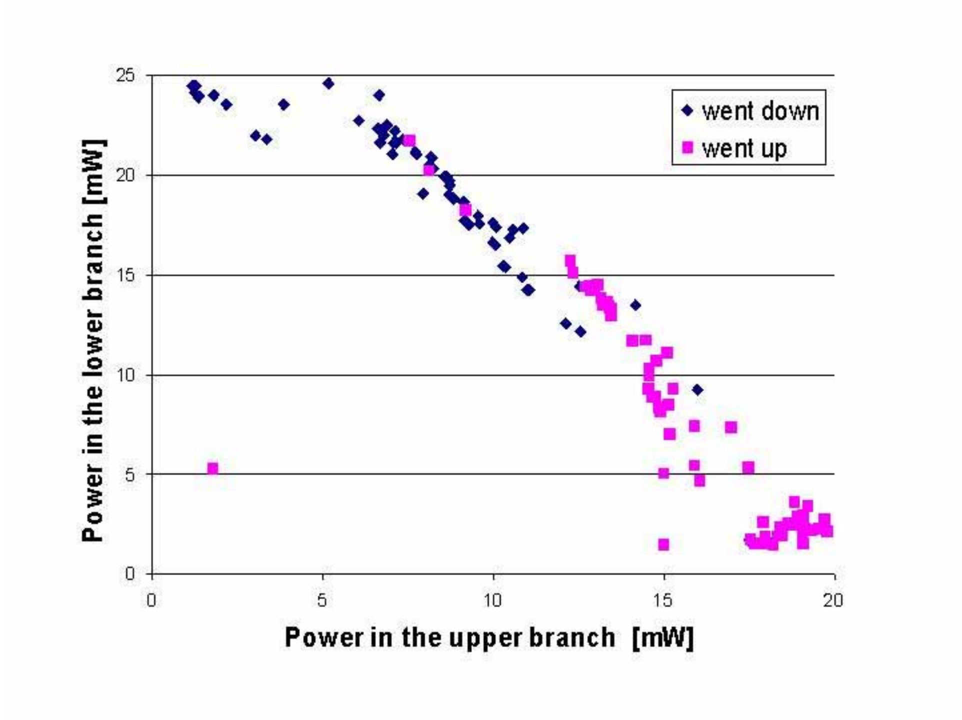

Fig. 3. Particle distribution between the upper and the lower waveguide branch with respect to the output power of the two branches at the time when the particle is in the junction region. Fibre output power was about 165 mW.

4. Conclusion

In this paper, a novel optical method for particle sorting and manipulation has been presented. We have shown that polystyrene microspheres can be reliably sorted above a Y-branched optical waveguide by simply changing the power distribution between the two branches. To achieve this we used a simple mechanical method. In future on-chip systems, this could ultimately be replaced by other methods like integrated electro-optic switching or wavelength-dependent routing. Two consecutive particles guided down the multimode trunk of the Y-junction can be reliably separated and sent down the two different branches if their separation distance is greater than some minimum value. This minimum separation is set by the given geometry and the power used. The device fabrication and separation method itself is very simple, and provides a convenient planar geometry for integrated microfluidics. Several parameters are available to be adjusted to optimise and tailor the device for a variety of applications, and the fabrication technology involves materials and processes that can easily be combined with other methods used for particle manipulation.

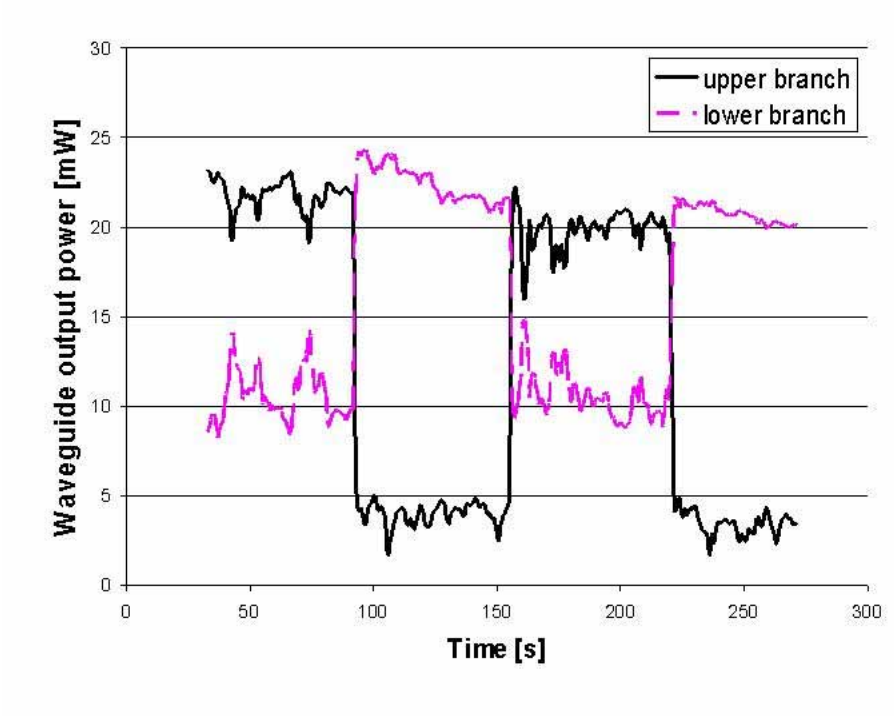

Fig. 4. Output power of the upper and the lower branches of the Y-branched waveguide as the fibre is flipped between the two chosen positions. Fibre output power was about 165 mW.

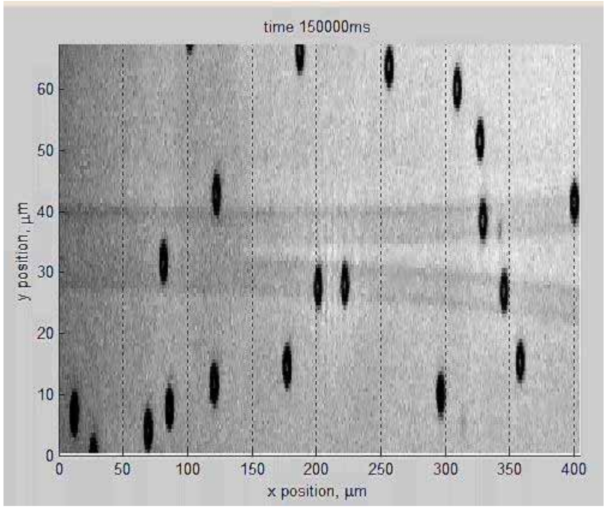

Fig. 5. Movie (2.0 MB) of the sorting of polystyrene microspheres above a Y-branched waveguide. The aspect ratio has been changed for convenience, thus the spheres appear elliptical.

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