Optofluidic tweezer on a chip

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A novel method to realize an optical tweezer involving optofluidic operation in a microchannel is proposed. To manipulate the optical tweezer, light from an optical fiber is passed through both PDMS (polydimethylsiloxane)-air surface lenses and an optofluidic region, which is located in a control channel. Two liquids with different refractive indices (RIs) are introduced into the control channel to form two different flow patterns (i.e., laminar and segmented flows), depending on the liquid compositions, the channel geometry, and the flow rates. By altering the shapes of the interface of the two liquids in the optofluidic region, we can continuously or intermittently control the optical paths of the light. To demonstrate the functionality of the proposed method, optical tweezer operations on a chip are performed. Changing the flow pattern of two liquids with different RIs in the optofluidic region results in successful trapping of a 25 μm diameter microsphere and its displacement by 15 μm . © 2010 American Institute of Physics. [doi:10.1063/1.3509436]

I. INTRODUCTION

In recent years, various types of functional components have been integrated into microfluidic devices for liquid handling,¹ temperature regulation,² and signal detection,³ resulting in the realization of principal concepts of lab-on-a-chip design such as reduction of sample and reagent volumes, miniaturization of device, and easy operation in biological and chemical analyses. Among these integrated components, optical elements, particularly for a fluorescence-based scheme, are the most crucial for the detection in microfluidic devices. Integrated optical elements for fluorescence detection consisting of an optical fiber, cylindrical lenses, and various sensors showed comparable performance to conventional equipment.⁴ On the other hand, optical elements having liquid characteristics such as flexibility, different refractive indices, and movement with surface tension were proposed and utilized for an on-off switch-type device,⁵ a variable-focus liquid lens controlled through electrowetting,⁶ and deformation of the thin film enveloping the liquid.⁷ In recent reports, the liquid optical element concept has been applied to microfluidics with a concept called “optofluidics” and used in dye laser,⁸ interferometer,⁹ spectroscopic sensor,¹⁰ photonic crystal,¹¹ tunable liquid-core/liquid-cladding optical waveguides,¹² and tunable on-chip lenses.^{13–15} Taking advantage of the liquid characteristics in the microchannel, optofluidics can be further applied to various on-chip optical elements. One of the applications is an optical tweezer. Optical tweezers use an optical force, which is exerted by the refraction and reflection of a focused beam of light, to trap and move objects ranging from nanometers to several micrometers in size. Since its introduction in 1986,¹⁶ the optical tweezer has become an important tool for noninvasive manipulation of a small particle in biological systems, especially in cell biology, with applications including cell fusion,¹⁷ mechanical cell measurement,¹⁸ and cell sorting.¹⁹ An optical tweezer, however, needs a relatively complicated, expensive, and large setup for precisely focusing and manipulating optical light paths. Furthermore, in more demanding applications such as trapping of multiple particles, cell fusion, and laser-based ablation systems, additional complex equipment are required. Although some groups are using an optical fiber as an alternative method for introducing the light for optical tweezer,^{20–22} they still need complicated setups to achieve small displacement

FIG. 1. Setup for microfluidic optical path control. (a) Schematic of the device indicating the control and sample channels. (b) Enlarged section of the microfluidic device shows the intersection of the optofluidic region and the light path. [(c) and (d)] By changing the flow rates of two liquids with different RIs, the flow patterns in the optofluidic region are deformed to control the light and move trapped microsphere in the direction along the flow axis in the sample channel.

of a microsphere. In this study, we propose an “optofluidic tweezer” in which optical paths emitted from an optical fiber are controlled in a device using microfluidic operations of liquids with different refractive indices (RIs). Since light is introduced using an optical fiber and light paths are manipulated using only liquid movement, optical tweezer operations are performed without any optical microscope and precise manipulation equipment.

II. THEORY

An optical tweezer traps a spherical particle in a surrounding medium using a principle based on the conservation of light momentum before and after refraction of incident light. Since light has a small amount of mass, the momentum change of light generates a force against a particle in the opposite direction of the momentum change according to the law of conservation. As a result, the sum of the forces moves the particle into the optical axis and the particle can be trapped.^{23,24} With a high numerical aperture (NA) optical system, in which light incident to the particle has a large angle with respect to the optical axis, forces acting on the particle direct it to the optical focal position where it can be trapped. In this study, however, the particle was pushed against the microchannel wall because of a limited low-NA concentrated light. In fact, it is difficult to design high-NA concentrated light with a large-diameter optical fiber without significant aberration.

The setup for microfluidic optical path control is illustrated in Fig. 1. Two types of microfluidic channels, i.e., a channel for sample introduction and another for controlling optics, and PDMS (polydimethylsiloxane)-air surface cylindrical lenses are embedded on a PDMS-based microfluidic device. Light is introduced into the optical elements by inserting an optical fiber into the fiber inlet on the device. The optofluidic region has a triangular shape located at the intersection of the

optical paths from the fiber and the control channel [Fig. 1(b)]. The triangular shape is used to change the focusing point in the direction along the flow axis in the sample channel, i.e., perpendicular to the optical element axis. Two liquids with different RIs are introduced through two inlet ports of the control channel. These liquids exhibit laminar or segmented flow, depending on the channel geometry and the combination of the liquids. By changing the flow rates, the flow patterns in the optofluidic region are deformed, controlling the light traveling through that area. When laminar flow is obtained, the boundary between the two liquids can serve as laminar flow (fluidic) lenses by which the optical paths can be continuously controlled. On the other hand, intermittent control is possible in the case of segmented flow. In our previous work, on-chip PDMS lenses with three cylindrical aspherical lens surfaces were developed.⁴ The same method was employed for the calculation of lens surfaces. The commercial optical design software CODE V[®] (Optical Research Associates) was used for computer-assisted optimization to concentrate the beam energy by making beam waists as narrow as possible and to simulate optical paths with different RIs of liquids flowing in the optofluidic region.

III. EXPERIMENTAL METHODS

The device was fabricated with conventional PDMS replica molding. A chromium mask used for photolithography outlined the fiber inlets, PDMS lenses, control channels, optofluidic region, and sample channel, which were all fabricated together. The depth of all structures was 125 μm , which was set to the outer diameter of a standard optical fiber. The width of the sample channel was 70 μm . To observe optical paths, a fluorescent dye (EpoDye, Marumoto Struers K.K.) was mixed with the PDMS (fluorescent PDMS). One of the ends of the optical fiber was inserted into the fiber inlet of the device. The other end was connected to a mercury lamp through a blue transmission filter (U-MNIB2, Olympus Corporation) for light path visualization. For the tweezer, a laser diode module (L9399-0, Hamamatsu Photonics K.K.), which emits 1 W of 826 nm light and connected to a multimode optical fiber with a core diameter of 60 μm , was employed. To change the optical paths by laminar flow, two kinds of silicone oil, 1,1,3,5,5-pentaphenyl-1,3,5-trimethyltrisiloxane (PDM-7050, AZmax Co.) and bis(tridecafluoro-1,1,2,2-tetrahydrooctyl) tetramethyldisiloxane (SIB1816.0, AZmax Co.), with refractive indices of 1.588 and 1.337, respectively, were introduced through the inlet port. In the case of segmented flow, PDM-7050 and fluorinert (FC-40, Sumitomo 3M Ltd., RI=1.29) were used. Laminar and segmented flows were obtained using a pressure-driven pump (My Flow, ARBIOTEC, Ltd.). Initially, pressure was applied to each port at 100 kPa and then decreased on one side of the port in order to deform the interface of laminar flow. A 25 μm polystyrene microsphere (Polysciences, Inc.) was introduced from the sample channel port for the tweezer experiment.

IV. RESULTS AND DISCUSSION

The results of optical path control with the laminar flow using fluorescent PDMS [Figs. 2(a) and 2(b)] with their corresponding simulated optical paths [Figs. 2(c) and 2(d)] are shown in Fig. 2. Since the optical lenses are cylindrical, the light in perpendicular direction to the device surface cannot be concentrated. To minimize the expansion of perpendicular direction light, the distance between the edge of the optical fiber and the position of the light concentration must be small. Although an optical magnification should be as small as possible to trap small particle, a minimum optical magnification we can achieve in this study was 0.5 times due to the restriction of the distance. The light from the optical fiber with a core of 60 μm in diameter was concentrated to 30 μm with the 0.5 times magnification optics in the simulated result [Figs. 2(c) and 2(d)]. The light emitted from the optical fiber was filtered through a blue transmission filter. Green fluorescent light from the PDMS was observed using a fluorescence microscope. Dotted lines indicate axes of the optical element. The beam waist in the fluorescent PDMS was about 30 μm , which shows good agreement with the simulated results.

In Fig. 2, silicone oil with RI=1.58 was introduced from the left hand side of the control channel, while silicone oil with RI=1.33 flowed from the right. Generally, whether the two liquids

FIG. 2. Visualized optical paths of fluorescent PDMS and simulation results. The flow rate of silicone oil with RI=1.33 is higher in (a) and (c), while (b) and (d) show a higher flow rate of silicone oil with RI=1.58. Patterns of the light paths through each PDMS multiaspherical lens and microfluidic optical element showed good agreement with the simulated ones.

will form a laminar flow or droplets strongly depends on the channel structure, the kind of liquids used, and the flow rate.²⁵ In fact, it was difficult to form a laminar flow using liquids that have a large difference in surface tension such as oil and water. In this experiment, different types of silicone oil driven by approximately 100 kPa pressure for higher flow rate and 50 kPa for lower flow rate achieved stable laminar flow within a short period.

The optical paths were successfully controlled using the RIs and shapes of the liquids inside the channel. Patterns of the light paths through each PDMS multiaspherical lens and microfluidic optical element showed good agreement with simulated ones. Laser diode light with a wavelength of 826 nm was used for this simulation. A chroma aberration, which can cause critical blurriness in image optical elements, does not affect this setup, which was intended only for concentrated light paths.

When the flow rate of the left side channel is higher than the right, the light is concentrated above the optical element axis, as shown in Fig. 2(c). Slower flow rate on the left side channel resulted in a narrow laminar flow of silicone oil (RI=1.58), which shifted the position of light concentration to about 10 μm below the optical element axis, as shown in Fig. 2(d).

This device was employed as an optical tweezer system. For laminar flow, a different pair of silicone oil (RI=1.58 and 1.33) was used (Fig. 3). Dotted circle in Fig. 3(b) indicates the initial positions of the microsphere depicted in Fig. 3(a). Bright regions in the sample channel indicate the trapped microspheres, which scatter the high-intensity light when positioned along the optical paths. The optical paths were controlled in the direction along the sample channel, i.e., perpendicular to the optical element axis, and a microsphere was successfully displaced by about 15 μm . In this optical configuration, the pushing light pressure was stronger than the pulling pressure due to the small NA of the concentrated light, thus the bead is trapped when it is pushed against a sidewall of the sample channel. The light power irradiated to the microsphere can be estimated from the actual power of light and the calculated expansion of light in the perpendicular direction to the device surface. The actual power of light from the edge of the optical fiber was 728 mW. Only 10% of light can be irradiated to 25 μm microsphere due to the expansion of the light. Furthermore, a loss with a reflection and a scattering of the light at the air-PDMS surface must be

FIG. 3. Optical tweezer operation by laminar flow. Laser light was manipulated to displace the microsphere shown as bright spots. In (b), the initial position of the microsphere in (a) is indicated by a dotted circle.

considered. Since the loss with a smooth PDMS surface is less than 1%, the loss in this device can be roughly estimated to be about 5%. With this calculation, the light power irradiated to the microsphere is estimated to be about 70 mW.

For segmented flow (Fig. 4), silicone oil (RI=1.58) and florinert (RI=1.29) were introduced through each channel port, resulting in the formation of droplets due to the large difference in their surface tensions. The movement of a trapped microsphere with segmented flow from 0 to 40 ms is shown in Fig. 4. A 15 μm displacement of the microsphere can be achieved with segmented flow as well as laminar flow. First, the optofluidic region was filled with silicone oil (RI=1.58) and the microsphere was trapped at a position below the optical element axis [Fig. 4(a)]. After 10 ms, a droplet of silicone oil (RI=1.33) filled the optofluidic region, and while the optical path shifted above the optical axis, the microsphere remained at its initial position because the shift of the optical path was faster enough than the moving velocity of the microsphere against a resistance of liquid. Scattered light from the microsphere was not observed because the optical paths and the microsphere position were not aligned. After 40 ms, with the optofluidic region still filled with silicone oil (RI=1.33), the microsphere moved to optical paths concentrated position due to the force of the light attracting the microsphere and the scattered light from the microsphere was observed again. From the velocity of the microsphere, which is about 0.5 mm/s, the hydrodynamic force exerted on the microsphere can be calculated using Stokes' law and found to be 235 pN, which is sufficiently strong for the use in biological applications. Strictly speaking, adhesive and friction forces between the microsphere and the channel wall must be considered to calculate the force to move the microsphere. We estimated these forces small enough because there was no stiction observed when the light was turned off.

Since a 60 μm optical fiber was used in this study, the optical path can be concentrated into 30 μm width with 0.5 times magnification optical system in this device. Smaller particles can be trapped by using an optical fiber with a smaller core diameter and connecting it to a high-power laser or a liquid dye laser integrated into a microfluidic device.

FIG. 4. Movement of a trapped microsphere with segmented flow from 0 to 40 ms. At 0 ms, the microsphere was trapped just below, in the photo, the optical element axis and the optofluidic region was filled with silicone oil (RI=1.58). After 10 ms, the optical path moved upper when a droplet of silicone oil (RI=1.33) filled the optofluidic region, but the microsphere remained at its initial position. At 40 ms, the microsphere moved to optical path concentrated position and the scattered light from the microsphere was observed again.

In this study, the optical paths were controlled using two kinds of silicone oils with RIs of 1.58 and 1.33. Larger displacement and more effective light path control for imaging and detection can be achieved by using liquids with a large difference in their RIs. Since the lowest RI fluid is air, the study of interface behaviors of air and high-RI liquids in the microchannel by variation of driving pressures, channel structure, and surface property is important for further applications.

V. CONCLUSIONS

Optical paths are successfully controlled using microfluidics and the optofluidic method has been applied to optical tweezers. A 25 μm diameter microsphere is trapped and displaced by 15 μm after changing the flow pattern of liquids with two different RIs in the optofluidic region. The force required to move the microsphere is calculated by controlling the optical paths with segmented flow. Compared to the advantages of conventional optical setups, advantages of this device include easy positioning, alignment, and handling. The introduction of a single-mode fiber and liquids with large RI difference will enable the use of this device for various optical applications. With a combination of conventional optical tweezer equipment, this method can be used for more complicated applications.

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