Adapting optical fields for particle manipulation on a chip

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Using silicon photonic devices to tailor optical fields results in a functional, potentially low-cost way to manipulate particles on a chip.

Optical tweezers have been used by biologists as a laboratory tool to optically manipulate small particles such as DNA and cells for more than two decades. However, conventional optical tweezers require bulk optics (typically a large numerical aperture microscope objective lens) with precision alignment and mechanical position control to trap and move micron-sized objects. Ideally, one could optically trap and manipulate particles on a planar platform using integrated photonic circuits, potentially enabling value-added functionalities—such as label-free particle sorting—in a parallel, high-throughput manner that is compatible with lab-on-a-chip technology.

Using the surface wave of a planar waveguide to optically manipulate micron-sized particles was first demonstrated in 1996. The principle is based on the fact that optical surface waves in close proximity (within a few hundred nanometers) to the waveguide surface offer both the scattering force to propel particles longitudinally along the waveguide, and the gradient forces to confine particles vertically toward the chip and laterally toward the waveguide axis. Multiple micron-sized particles in diluted colloidal solution can be simultaneously trapped and transported on the surface of millimeter-long integrated waveguides on a chip without strongly perturbing the waveguide modes.

Building on this existing technology, we and others have over the past couple of years leveraged silicon photonic waveguides and microresonators to optically manipulate particles on a chip. Specifically, we demonstrated optical trapping and dropping of micron-sized polystyrene particles in water on silicon nitride-based waveguides as well as microring and microdisk resonators that are embedded in microfluidic channels on optofluidic chips. We chose the silicon nitride platform for its key merits of CMOS-compatible fabrication process, sufficiently high refractive index contrast to water, and transparency from visible to near-IR wavelengths. The microring and microdisk resonators provide a convenient means to tailor the surface optical fields at optical resonance wavelengths to optically trap, route, and switch particles in a wavelength-switchable manner.

We demonstrated optical manipulation of micron-sized polystyrene particles on silicon nitride microring and microdisk resonators using 1550nm wavelengths (see Figure 1). In the case of microring-based optical manipulation, our experiments demonstrated wavelength-dependent microparticles' add-drop filtering. That is, microparticles that are optically guided on a waveguide can be transported to the waveguide through-port at an off-resonance wavelength. Or, they can be transported and buffered in the microring traveling in round trips at a high-Q resonance wavelength. Also, they can be routed to the waveguide drop-port at a relatively low-Q resonance wavelength. The detailed mechanism concerning the particle dropping from the microring to the waveguide, and whether it is a deterministic or probabilistic process, is being further investigated experimentally and theoretically.

Unlike microring resonators that are typically single-mode devices, microdisk resonators usually support multiple whispering-gallery modes (WGMs). High-order WGMs exhibit multiple mode-field maxima along the radial direction of the microdisk, and potentially enable multiple particle trapping tracks.

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The extended mode-field distribution inside the microdisk also extends the particle trapping range. Our experiments demonstrated this using single wavelengths through exciting various high-order WGMs. We also demonstrated active switching of the microparticle traveling tracks while the particles were guided in the microdisk by tuning the laser wavelength from one WGM to another.

In summary, we are at the dawn of a new type of planar optical manipulation technology that can potentially revolutionize the lab-on-a-chip platform for biological and medical research. The silicon photonic waveguide and microring and microdisk resonator technologies for optical manipulation can be regarded as basic building blocks offering particle trapping and routing functionalities that can be readily controlled by the laser wavelength. However, further work is needed to demonstrate particle manipulation at an improved speed. That, in turn, would enable high-throughput particle manipulation that can be sensitive to particle size, shape, surface quality, elasticity, and refractive index. This would enable label-free particle sorting with high selectivity and accuracy (such as sorting cancerous cells from healthy cells), as well as better integration between integrated photonics and fluidics and lab-on-a-chip technologies. Only when such exciting interdisciplinary developments happen will the technology that we and others have innovated eventually find real social impact in the form of a new breed of particle circuits that might one day be used in the clinic, or at points-of-care.

Going forward, we plan to manipulate biological particles of micrometer and nanometer sizes on a silicon optofluidic chip. We will explore optofluidic particle sorting that could arrange particles in a label-free manner according to their morphologies. We will work to expand the CMOS photonic components library for particle manipulation, such as controlling particles on waveguide tapers and multimode interference devices, and using these components along with waveguides and microresonators as building blocks for future functional optofluidic integrated circuits.

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References

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