On-chip supercontinuum optical trapping and resonance excitation of microspheres

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We demonstrate the simultaneous optical manipulation and analysis of microscale particles in a microfluidic channel. Whispering gallery modes (WGMs) in dielectric microspheres are excited using the evanescent field from a silicon nitride waveguide. A supercontinuum source is used to both trap the microspheres to the surface of the waveguide and excite their resonant modes. All measurements are in plane, thus providing an integrated optofluidic platform for lab-on-a-chip biosensing applications. © 2010 Optical Society of America

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Optical trapping has been demonstrated as a critical tool for the manipulation of microscale particles for many biological applications [1]. Furthermore, it has been shown that the combination of optical trapping forces with the precise control provided by microfluidics can produce optofluidic devices with increased functionalities [2]. Recent progress in this area has included various devices to generate the near field intensity gradients required to achieve optical trapping [3–6]. In most realizations of optical manipulation, a single narrowband light source is utilized. We show the use of broadband light to generate optical forces on an integrated structure as a tool for the characterization of microscopic objects. To demonstrate an application that takes advantage of the broadband nature of our source, we investigate the spectral response of trapped microspheres in a microfluidic environment.

The ability to simultaneously manipulate and characterize a single microscopic object is an important functionality for biomedical applications [7]. The platform demonstrated here utilizes both microfluidic flow and optical forces from a broadband source to position dielectric microparticles for individual analysis. Following transport within a microfluidic channel, the particle's position is controlled by optical forces generated by a waveguide's evanescent field. These radiation forces, which are due to changes in the incident light momentum, can be decomposed into transverse and longitudinal components as shown in Fig. 1. The decay of the evanescent field intensity results in a gradient trapping force that attracts the particle to the waveguide [8]. Particle scattering and absorption of the incident light momentum leads to a radiation pressure force that propels the particles in the direction of light propagation [8]. Since the trapping light source is broadband, the spectral response of the trapped microparticle can be used for characterization.

Several design parameters were considered to ensure broadband operation and the generation of strong optical forces. The waveguiding material is stoichiometric silicon nitride (Si_3N_4), which has low absorption in the visible and near infrared and allows fabrication of low-loss waveguides [9]. Silicon nitride's high refractive index ($n=2.0$) relative to water ($n=1.33$) leads to strong gradient-trapping forces. The dimensions of the waveguide are 200 nm tall by 2 μm wide, and nanotapers at the ends of the waveguides ensure that light couples into the fundamental quasi-TM waveguide mode. The light source is a commercially available supercontinuum (SC) source (Fianium SC-450) that generates a broad output spectrum (500 nm−2.0 μm) and high average powers (~4 W). Due to the source's high degree of spatial coherence [10], the SC light can be efficiently focused down by a tapered lens fiber to mode match with the waveguide nanotapers. The input spectrum of the SC source along with the waveguide transmission spectrum is shown in Fig. 2. We measure only a 10 dB power loss between the input and the output of the waveguide while efficiently coupling light at wavelengths across the near infrared spectrum.

The optofluidic devices were fabricated using standard microlithography techniques. Details on the waveguide fabrication can be found in [9], where the same process was used with demonstrated waveguide propagation losses of 0.1 dB/cm in the near in-

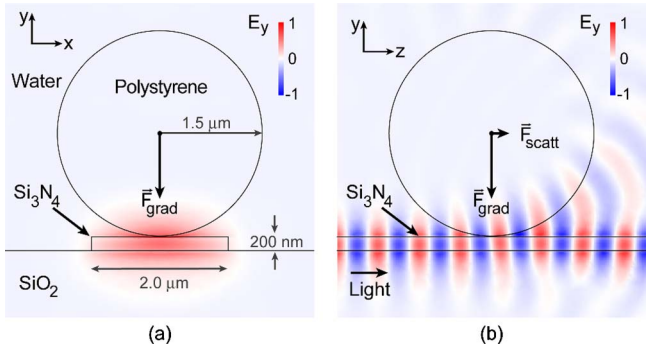

Fig. 1. (Color online) 3D simulation results for the electric field (E_y) profile of the quasi-TM mode at a wavelength of 850 nm in a silicon nitride waveguide. The optical forces on a dielectric microsphere can be decomposed into a transverse gradient force (F_{grad}) that traps the sphere to the waveguide surface and a longitudinal force (F_{scatt}) that propels it along the direction (z axis) of light propagation.

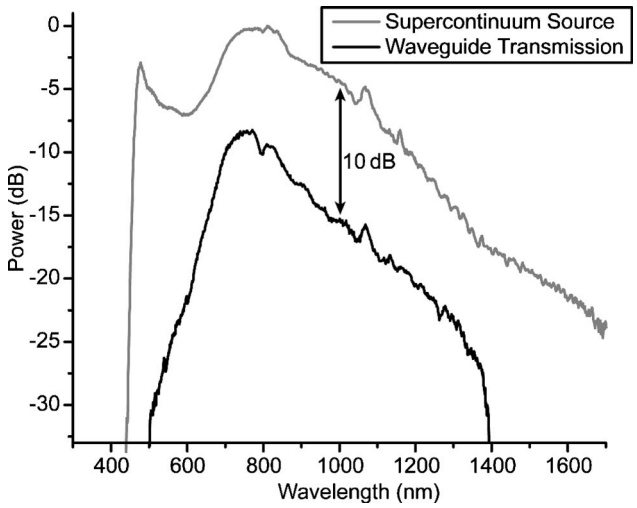

Fig. 2. Spectra of the supercontinuum source and waveguide transmission showing efficient broadband coupling to the waveguide from 700 nm to 1400 nm.

frared. Microfluidic channels with 30 μm height and 300 μm width were fabricated from polydimethylsiloxane (PDMS). Inlet and outlet ports for fluids were punched through the PDMS, and the channels were aligned orthogonal to the waveguide to allow passing microspheres to interact with the waveguide's evanescent field.

The experimental procedure requires coupling broadband light onto the photonic chip and measuring the waveguide's transmission spectrum. The free-space output of the SC source is coupled into a single-mode polarization-maintaining fiber (Thorlabs P5-1550PM). The tapered fiber is butt coupled to the waveguide input and oriented to excite the waveguide quasi-TM mode. The waveguide output is collected with an achromatic microscope objective (Olympus Plan 40×) and passed through a polarization analyzer (Newport 10GL08). The light is then coupled into a multimode fiber and its spectrum measured with a spectrometer (Ocean Optics HR2000). Polystyrene microspheres (Duke Scientific $n=1.59$) of various diameters are prepared in deionized water with surfactant to prevent aggregation. The microsphere solution is injected into the microfluidic channels, and flow velocity is controlled by adjusting the height of the microsphere solution reservoir.

Microspheres of various diameters were flowed through the microfluidic channel and were optically trapped and transported by the waveguide's evanescent field. Figure 3, along with its accompanying video (Media 1), shows the manipulation of 3-μm-diameter particles using broadband light with ~10 mW of guided power. Optically induced damage to biomolecules should not be a concern for this system due to the relatively low optical powers used along with operation in the low-absorption near infrared regime [11]. Roughly 25% of the microspheres in this video are trapped by the waveguide; this trapping efficiency can be improved by decreasing the channel height, increasing the optical power, or slowing the flow speed. The optical forces on a polystyrene microsphere were calculated using 3D finite-element

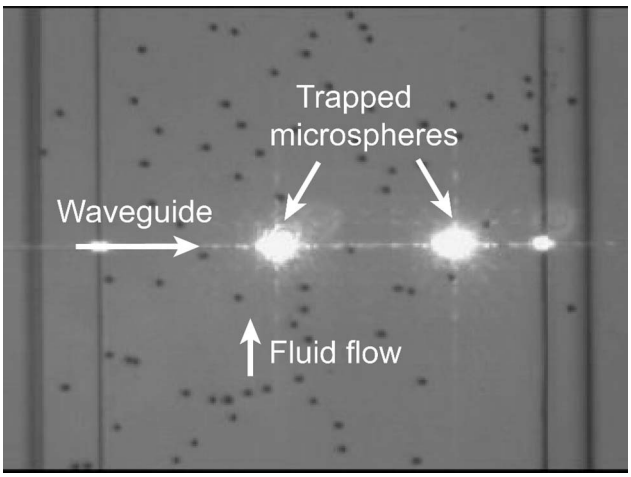

Fig. 3. Optical trapping and transport of 3-μm-diameter polystyrene microspheres in a microfluidic channel using a supercontinuum broadband light source. Video (Media 1) ⟨medioref⟩ shows optical trapping of several polystyrene microspheres using ~10 mW of guided power. Playback is 2× real time.

analysis with the Maxwell stress tensor formalism [3]; the simulated mode results are shown in Fig. 1. For a 3-μm-diameter particle with 5 nm waveguide separation and 850 nm trapping wavelength, the gradient force and scattering force are 1.5 nN/W and 0.21 nN/W, respectively. These values are in good agreement with previous results obtained for silicon nitride waveguides [12]. Trapping of microspheres with diameters ranging from 500 nm to 20 micrometers was observed.

Particles that are trapped by the intensity gradient of the broadband light source can be simultaneously analyzed by measuring the spectrum of the waveguide transmission. Figure 4 shows the transmission spectrum of the waveguide while an 18 μm polystyrene microsphere is trapped. The curve is normalized to the spectrum when no particle is present. The transmitted spectrum displays a series of dips that correspond to the whispering gallery mode (WGM)

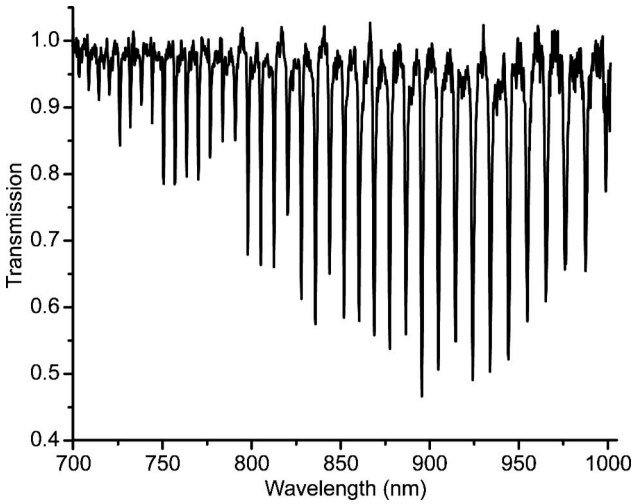

Fig. 4. Waveguide transmission spectrum showing WGM resonances of an optically trapped 18-μm- diameter polystyrene microsphere with quality factors of ~2,000.

resonances of the trapped microsphere. Wavelengths that are integer multiples of the sphere circumference build up as a result of total internal reflection at the boundaries of the sphere. Figure 5 shows the free spectral range measured using microspheres of different diameters. By controlling the microsphere concentration and fluid flow velocity, we trap single microspheres at a time to simplify the analysis of the transmitted spectra. The solid lines represent the theoretical curves for WGM resonances calculated using the known refractive indices of the materials and the measured size of the particles [13]. The agreement between the data and the theoretical curves affirms that light is coupling into the fundamental resonant cavity modes of these microspheres. Therefore, not only is the broadband light being used to physically manipulate the particle, but it also provides a spectral signature of the interaction, allowing analysis of the particle. Changes in the resonance wavelength and linewidth can be used to sense changes in the local fluidic environment such as adsorption of biomolecules to the microsphere's surface.

We have demonstrated the simultaneous optical trapping, manipulation, and analysis of single microscale particles using silicon nitride waveguides and a broadband supercontinuum light source. To the best of our knowledge, this is the first time a white-light source has been used for integrated optical trapping, which may enable new lab-on-a-chip biosensors with increased functionalities. Several broadband particle-characterization methods could be used in conjunction with the technology demonstrated here, including fluorescence and scattering spectroscopy [14] as well as coherent anti-Stokes Raman spectroscopy [15]. Measurements of WGMs in various structures have been used successfully to detect the binding of single biomolecules [16]. To date, coupling light into these high-quality-factor devices is done using a tapered optical fiber or a prism, and therefore a complete integrated system cannot be fabricated using standard photolithography techniques. The use of in-plane waveguide excitation of flowing microspheres presents a potential method to fully integrate WGM-based biosensors.

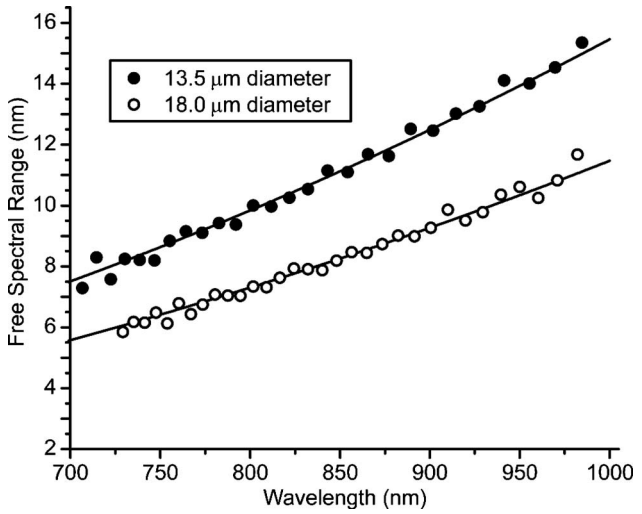

Fig. 5. Experimental (circles) free spectral range in microspheres of different diameters with theoretical (solid lines) curves for WGMs in spherical cavities.

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