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Hollow-core photonic crystal fiber based multifunctional optical system for trapping, position sensing, and detection of fluorescent particles

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We demonstrate a novel multifunctional optical system that is capable of trapping, imaging, position sensing, and fluorescence detection of micrometer-sized fluorescent test particles using hollow-core photonic crystal fiber (HC-PCF). This multifunctional optical system for trapping, position sensing, and fluorescent detection is designed such that a near-IR laser light is used to create an optical trap across a liquid-filled HC-PCF, and a 473 nm laser is employed as a source for fluorescence excitation. This proposed system and the obtained results are expected to significantly enable an efficient integrated trapping platform employing HC-PCF for diagnostic biomedical applications. © 2012 Optical Society of America

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Optical trapping methods have turned out to be a common tool in medicine and biology [1,2]. They are broadly used for manipulation, diagnosis, and alteration of cells, microorganisms, and macromolecules [2–4]. Optical trapping methods have good prospects within the fields of cell signaling and tissue engineering [5]. Recently, there have been significant efforts toward system miniaturization and reduction of sample consumption [6,7]. A hollow-core photonic crystal fiber (HC-PCF) can achieve guidance in air by using the Bragg reflection from a periodic fiber cladding structure and has the potential of being a medium for efficient biosensing application due to the increased light-matter interaction in the hollow core [8,9]. All-optical control of particles inside water-filled HC-PCF is proposed and illustrated [10]. A few groups have examined the possibility of various ultrasmall optical devices by transversely probing light across the length of microstructured HC-PCF [11,12]. Recently, we have investigated numerically and optimized the use of transversely probed HC-PCF for optical trapping applications [13]. Further, an integrated HC-PCF transverse optical trapping system for optical manipulation and detection of micrometer-sized fluorescent particles is proposed and illustrated [14].

In addition to component miniaturization, it is also advantageous to explore a multifunctional trapping system with the incorporation of additional optical functions such as imaging, diagnosis, and sensing into the basic trapping scheme. The use of a multifunctional optical system may have high potential within single-cell analysis, since parallel measurements provide good statistics. This Letter, in this context, details the proposed concepts and experimental demonstration carried out with respect to multifunctional trapping employing HC-PCF. Illustrations of multifunctions (optical modalities) such as imaging, position sensing, and fluorescence detection are carried out sequentially and simultaneously with micrometer-sized fluorescent beads as samples.

The schematic diagram of the experimental setup for the multifunctional optical trap employing HC-PCF is

shown in Fig. 1. Trapping light was delivered by a cw Ti:sapphire laser [Coherent Mira 900B, pumped by a Coherent Verdi V-10 frequency-doubled Nd:YVO₄ laser (532 nm)]. A Gaussian laser beam (TEM₀₀ profile) is passed through a beam collimator unit (formed by lenses L₁ and L₂) so as to expand and collimate the beam to the required beam size, before directing it to the back aperture of the trapping objective (MO₁) (Newport M-40X/0.65) using a beam steering unit (formed by mirrors M₁ and M₂) and mirror M₃. A fiber-coupled diode-pumped solid-state (FC-DPSS) laser (output power ≈3 mW) with a wavelength of 473 nm was employed for fluorescence excitation. The signal emerging from the sample chamber is collected using a detection objective (DO) (Newport M-20X/0.4) at its back focal plane and is directed through mirror M₄. An optimum numerical aperture (NA) DO is chosen in order to collect more light over a larger depth of focus.

Three sets of planes are defined: specimen plane (P), conjugate back focal plane (P^I), and conjugate specimen plane (P^{II}). The trapping and the fluorescence excitation laser beams are probed through the sample chamber. The signal emerging from the DO is directed toward a high quantum efficiency spectrometer (QE 65000, Ocean Optics) operating with a spectral range of 200 to 1100 nm, using a microscope objective lens. The digital CCD camera (PL-A741, PixeLINK) is used for acquiring images and

Fig. 1. Schematic of experimental setup employed for the multifunctional trap.

is triggered under computer control to take bright field videos or images of the sample at the desired sampling rate. The detection signal is also demagnified using a pair of lenses [plano-convex lens (L_3) and objective lens (L_4)] to project it onto a position detector. The focal distances of L_3 and L_4 are 200 and 25.8 mm, respectively. A quadrant photodiode (QPD) detects the changes in the forward scattered light pattern with the changes in the particles position, and these changes are measured using a personal computer (PC)-based oscilloscope and analyzed using PicoScope 3204 (Pico Technology Limited) software installed in the PC. The QPD outputs a voltage signal corresponding to displacement of the bead along the x and y axes (V_x and V_y), thereby indicating the position/location of the bead.

The HC-PCF considered here is designed for air-filled operation at 1550 nm (Crystal Fibre A/S). The hollow core has a diameter of $10.9\text{ }\mu\text{m}$ surrounded by a microstructure comprised of eight periods of hexagonally packed cylinders with a period of $3.8\text{ }\mu\text{m}$ with a filling fraction of around 90%. The fiber is cut into segments of $\approx 6\text{ cm}$ length, and one end of the fiber is cleaved carefully using a fiber cleaver to produce a flat surface. A 2–3 mm wide channel, tightly sealed on top with a coverslip, with a volume of a few microliters is formed on a standard microscope slide. The HC-PCF is introduced through the side of the channel formed. The sample chamber is mounted on a three-axis translational stage that provides a stable and smooth translation mount for the sample chamber. The sample chamber and the axis along the length of fiber are adjusted to be perpendicular to the probing laser beam. The sample solution containing $2\text{ }\mu\text{m}$ green fluorescent microspheres (internally dyed polymer beads) dispersed in water and is transferred to the sample chamber through the sides of the channel.

The central wavelength of the Ti:sapphire laser is tuned to 800 nm and is operating at 220 mW output power. The beam is expanded as explained in the earlier section for filling the back pupil of the microscope objective lens. The HC-PCF in the sample chamber is adjusted such that the probing beam points exactly toward the cleaved end of the fiber (i.e., in the transverse direction). The microparticles around the fiber end face are initially attracted laterally and trapped; subsequently they are driven to the core of HC-PCF. Movement of particles close to the fiber end is captured and imaged through the DO and is directed to the CCD camera, spectrometer, and QPD as shown in Fig. 1. Figure 2 shows images of the particle being trapped and guided into the core of the HC-PCF, acquired with a CCD camera by probing the laser beam transversely to the central core.

The fluorescence of the particles trapped at the region was measured and characterized simultaneously by exciting the region with a fiber-coupled blue laser (wavelength, $\lambda = 473\text{ nm}$), as shown in Fig. 1. Here, the excitation laser is directed to the trapping region using a pellicle beam splitter (BS_1). The spectrometer collects the light emerging from the DO through the transfer optics. When there is no particle in the core of HC-PCF, the collected spectra have peaks corresponding to the trapping light beam ($\lambda = 800\text{ nm}$) and fluorescence excitation source ($\lambda = 473\text{ nm}$) only. With the fluorescent

Fig. 2. (a), (b) Images of a particle being trapped within an HC-PCF (solid white lines encircling particle positions are guides for the eyes).

polymer bead trapped and guided to the trapping region inside the central core of the HC-PCF, the collected spectra also contain the emitted fluorescent signal. In our experiment, spectra are acquired at time intervals of 2 s each, and the obtained result is shown in Fig. 3.

The variations in the fluorescent signal intensity with respect to wavelength at different intervals of time are expanded in the inset of Fig. 3. The scattered trapping light from the sample chamber, the fluorescence excitation, and the emission lights are clearly observed in the presence of the particle. The fluorescence intensity measurements are carried out continuously during the trapping process. For convenience, the data at instances $t = 0, 2, 4$, and 6 s are shown in Fig. 3. The fluorescent intensity is related to the location of the particle with respect to the optical axis. As the particle gets trapped and comes extremely close to the optical axis, fluorescent intensity becomes a maximum (at $t = 2\text{ s}$ in Fig. 3). As the particle moves away from the optical axis, the emitted fluorescent signal decreases gradually, and there is no significant fluorescent emission (e.g., at $t = 6\text{ s}$ in Fig. 3) as the particle moves completely away from the trapping

Fig. 3. (Color online) Optical spectrometer data obtained at the back focal plane of the DO at time intervals of 2 s. In this configuration, an 800 nm laser is used to trap the bead. The 473 nm laser is used as the fluorescence excitation source. Inset: The fluorescence emission region is enlarged.

Fig. 4. (Color online) (a) Schematic of the setup employing QPD for particle detection, yielding electrical signals proportional to the particle displacements. QPD signals corresponding to the particle positions along the (b) X and (c) Y directions and (d) Brownian motion of the trapped bead projected on the x - y plane.

region. Hence, the fluorescent signal gives an indication about the position of the particle around the trapping region with respect to the optical axis.

Position measurement of the trapped particle in the proposed scheme is carried out by employing the QPD based on a back focal plane (BFP) scheme. A focused light beam from the microscope objective (MO_1) passes through the sample chamber containing microspheres, where the diffracted light from the microspheres interferes with the undiffracted light. The light pattern at the BFP of the detection objective (DO) is projected onto the QPD detector by associated collection optics, as detailed in Fig. 1. The analog circuitry inside the QPD forms voltages V_x and V_y , corresponding to real X and Y positions of the trapped particle with respect to the center of trap. The linear position sensor module (Noah Corp.) employed in our experiment is based on a position sensing detector and outputs the necessary position information in terms of voltage. The particle tracking system employing the QPD is schematically represented in Fig. 4(a).

In order to convert the voltage signals to the actual displacement units, the QPD must be calibrated. Here, a $1\ \mu\text{m}$ polymer microsphere bead attached to the glass surface is used as the sample for position calibration. The obtained ratio of output voltage to the real displacement is found to be $\approx 86.43\ \text{mV}/\mu\text{m}$. The X and Y voltage signals are acquired using QPD concurrently with imaging (Fig. 2) and fluorescence measurements (Fig. 3) while the particle is being trapped at the central core of the HC-PCF. The obtained signals are shown in

Figs. 4(b) and 4(c). The X and Y voltage signals are converted to the displacement values based on the position calibration data. The Brownian motion of the trapped bead is reconstructed using the positional data, as shown in Fig. 4(d).

In summary, a novel multifunctional optical trap system is proposed and illustrated using HC-PCF. The multifunctional optical trap has multiple functionalities in terms of trapping, imaging, position sensing, and fluorescence signature characterization from a cell-like particle. The proposed scheme enables acquisition of various data either sequentially or simultaneously. This proposed scheme, when integrated into a device such as a heterogeneous biochip with built-in microfluidic delivery, is expected to offer diagnostic potential and synthesis functionalities for various biomedical applications, such as disease diagnosis.

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