An integrated hollow-core photonic crystal fiber transverse optical trapping system for optical manipulation and detection

Shinoj, V. K.; Murukeshan, Vadakke Matham

2012

Shinoj, V. K., & Murukeshan, V. M. (2012). An integrated hollow-core photonic crystal fiber transverse optical trapping system for optical manipulation and detection. *Journal of Applied Physics*, 111(2), 023106-.

<https://hdl.handle.net/10356/95212>

<https://doi.org/10.1063/1.3676248>

© 2012 American Institute of Physics. This paper was published in *Journal of Applied Physics* and is made available as an electronic reprint (preprint) with permission of American Institute of Physics. The paper can be found at the following official DOI: [<http://dx.doi.org/10.1063/1.3676248>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 07:28:24 SGT

An integrated hollow-core photonic crystal fiber transverse optical trapping system for optical manipulation and detection

V. K. Shinoj and V. M. Murukeshan

Citation: *J. Appl. Phys.* **111**, 023106 (2012); doi: 10.1063/1.3676248

View online: <http://dx.doi.org/10.1063/1.3676248>

View Table of Contents: <http://jap.aip.org/resource/1/JAPIAU/v111/i2>

Published by the [American Institute of Physics](#).

Related Articles

High selective two-dimensional Bragg resonators of planar geometry: Theoretical, computational, and experimental study

J. Appl. Phys. **112**, 114504 (2012)

Broadband switching functionality based on defect mode coupling in W2 photonic crystal waveguide

Appl. Phys. Lett. **101**, 151110 (2012)

Surface plasmon amplification characteristics of an active three-layer nanoshell-based spaser

J. Appl. Phys. **112**, 074309 (2012)

The corner effect in hexagonal whispering gallery microresonators

Appl. Phys. Lett. **101**, 141116 (2012)

ZnTe/GaSb distributed Bragg reflectors grown on GaSb for mid-wave infrared optoelectronic applications

Appl. Phys. Lett. **101**, 121909 (2012)

Additional information on *J. Appl. Phys.*

Journal Homepage: <http://jap.aip.org/>

Journal Information: http://jap.aip.org/about/about_the_journal

Top downloads: http://jap.aip.org/features/most_downloaded

Information for Authors: <http://jap.aip.org/authors>

ADVERTISEMENT

The advertisement banner for AIP Advances features a green and yellow background with abstract, flowing, wavy lines. The text 'AIPAdvances' is prominently displayed in the center, with 'AIP' in blue and 'Advances' in green. To the right of the text is a circular seal that reads 'Now Indexed in Thomson Reuters Databases'. Below the main text, there is a blue horizontal bar with the text 'Explore AIP's open access journal:' in white. To the right of this bar is a list of three bullet points: 'Rapid publication', 'Article-level metrics', and 'Post-publication rating and commenting'.

AIPAdvances

Now Indexed in Thomson Reuters Databases

Explore AIP's open access journal:

- Rapid publication
- Article-level metrics
- Post-publication rating and commenting

An integrated hollow-core photonic crystal fiber transverse optical trapping system for optical manipulation and detection

V. K. Shinoj and V. M. Murukeshan^{a)}

School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

(Received 12 July 2011; accepted 13 December 2011; published online 31 January 2012)

Optical manipulation, separation, and detection of biological cells have immense potential biomedical applications, for example, in disease detection. In this paper, we present optical manipulation and detection of micron sized fluorescent particles inside hollow-core photonic crystal fiber (HC-PCF) by transverse optical trapping. An optical trapping system is designed where a near-infrared laser light is focused using a microscope objective to create an optical trap across a liquid-filled HC-PCF. The fluorescent microsphere particles trapped in the core of HC-PCF using the laser induced optical force further undergo imaging and fluorescence spectroscopic analysis. It is illustrated that the proposed method can track the particle into a different medium using the optical trap as well. The obtained results indicate that this proposed method has tangible potential for developing HC-PCF based lab-on-a-chip bio/chemical sensors capable of detecting reagents in ultra low sample volumes. © 2012 American Institute of Physics. [doi:10.1063/1.3676248]

I. INTRODUCTION

Over the past few decades, ultrasensitive detection methods have become well recognized tools that play an enabling role in medical diagnostics.^{1,2} There are numerous studies on combining the ultrasensitive detection methods with different manipulation methods.^{3,4} Lab-on-a-chip (LOC) is a total analysis system introduced in the early 1990s that miniaturized large analytical devices.^{5,6} Every cell-based LOC has two main components: manipulation and detection units.⁷ Among the potential detection methods and principles, optical detection is the most common tool in modern chemical and biochemical analysis. Specifically, fluorescence detection appears to be superior regarding sensitivity and achievable limits of detection.⁸ The need for accurate, portable, and low cost analytical/diagnostic tools motivates the research and development of LOC. There had been significant advances in LOC technologies in the last two decades, and LOC applications can be regarded as one of the key growth industries of the 21st century.

Microstructured optical fibers (MOFs) consist of a two-dimensional periodic matrix of air inclusions that run along the length of the fiber.⁹ Hollow core photonic crystal fibers (HC-PCFs) are a special class of MOFs where light is guided within the central hole surrounded by smaller cladding holes that provide the bandgap confinement.¹⁰ High light-matter interaction cross section of the field energy and the sample material can be achieved with these fibers. Unlike conventional fibers, photonic crystal fibers are made of pure silica glass (SiO₂) without any doping. Hence they are biocompatible and chemically inert. HC-PCFs have been widely used for evanescent wave sensing or highly efficient sensing of biomolecules in the recent past, such as DNA, enzymes, antigen, antibodies, and proteins.^{11–14} The use of HC-PCF to

transmit light within a liquid core and to levitate dielectric particles is demonstrated.¹⁵ This motivates the research on the optical manipulation and detection capability of these fibers. In our previous work, we have demonstrated HC-PCF based fluorescent biosensors by immobilizing a sample solution inside the core of a HC-PCF.^{14,16} However, in that case, the immobilized sample cannot be used again. It will be advantageous to retrieve the sample from the fiber core after analysis and transfer it to another sample cell. To get control over positioning of such particles on the micron scale, independent of surrounding fluid, an appropriate micromanipulation technique is required. A number of non-contact micromanipulation techniques have already been proposed and the most promising one is dynamic micromanipulation using a laser beam with one or more focal points, known as the optical trapping method.^{17–19}

In this paper, novel optical manipulation and detection of fluorescent microsphere samples are performed using HC-PCF and optical trapping means. Here, the trapping laser beam propagates transversely through the liquid-filled HC-PCF cladding and focuses on the fiber axis (i.e., central core). The sample particles get attracted into the central core of HC-PCF due to the laser induced optical force and undergo different analyses. These particles are consequently moved into a different medium by translating the trap along the length of the fiber. This study may lead to consideration of HC-PCFs as ideal platforms for the investigation into optical manipulation and detection of biological species inside the central core. The proposed method will be particularly advantageous for biosensing applications where the reagent use is limited, such as analysis of rare or precious cells, and the sample environment is to be changed after study.

II. EXPERIMENTAL STUDY

The schematic of the experimental setup for transverse optical trapping inside a HC-PCF is shown in Fig. 1(a).

^{a)}Author to whom correspondence should be addressed. Electronic mail: mmurukeshan@ntu.edu.sg.

FIG. 1. (Color online) (a) Schematic diagram of HC-PCF based transverse optical trapping system and (b) actual prototype (laser beam propagation direction is shown in red arrows) Inset: Trapping region is expanded.

Trapping light was delivered by a continuous-wave Ti:sapphire laser (Coherent Mira 900B, pumped by a Coherent Verdi V10 frequency-doubled Nd:YVO₄ laser (532 nm)). The wavelength of the Ti:sapphire laser is centered at 800 nm and has a repetition rate of 80 MHz when operated in femto-second pulse mode. Gaussian laser beam (TEM₀₀ profile) passed through a beam collimator unit, which allowed controlling the divergence of the laser beam, and filled the back pupil of a microscope objective lens (Newport M-40X/0.65 (L₃)) to form an optical trap inside a sample chamber. Figure 1(b) shows a photograph of the optical setup. A picture of the sample chamber is shown in Fig. 2. The sample chamber is formed by placing two pieces of double sided sticky tape across the center of a standard microscope slide to form a 2–3 mm wide channel with a volume of around 50 μ l. A coverslip is positioned over the top of the tape, at right angles to the microscope slide, and tightly sealed, forming a channel with a volume of a few microliters. The sample chamber is mounted on a three-axis translational stage that provides a stable and smooth translation mount for the sample chamber. The deposition of sample solution is done

on one side of the channel and drawing of the solution is performed from the other side. The hollow-core PCF is introduced through the side of the channel. Now the sample chamber and the axis along the length of fiber are perpendicular to the probing laser beam. The image of the trapped particles is projected through a different objective lens (Newport, M-20X/0.4 (L₄)). The digital CCD camera (PL-A741; Pixelink, Ottawa, Canada) is used for acquiring data, and is triggered under computer control to take bright field videos or images of the sample at a desired sampling rate.

III. RESULTS AND DISCUSSION

The fiber considered here is a HC-PCF designed for air-filled operation at 1550 nm (Crystal Fiber A/S). The hollow core has a diameter of 10.9 μ m surrounded by a microstructure comprised of eight periods of hexagonally packed cylinders with a period of 3.8 μ m with a filling fraction of around 90%. The silica of the fiber has a refractive index of 1.45 and the cladding diameter is 125 μ m. The fiber is cut into segments of approximately 6 cm length and one end of the fiber is cleaved carefully using a fiber cleaver to produce a flat surface. The cleaved ends of the HC-PCF segments were dipped into water to allow the solution to be drawn into the fiber holes due to the capillary effect. The filling of liquid solution in the fiber holes is to ensure that the effect of capillary force to attract the particle toward the fiber holes is minimized. The sample solution containing fluorescent microspheres is transferred to the sample chamber through the sides of the channel. The sample used in our experiment is a 2 μ m diameter green fluorescent polystyrene bead (Duke Scientific Corp., USA) with a refractive index of 1.57 diffused in distilled water. These are internally dyed polymer beads.

Higher viscosity (η) of the liquid medium would impede the motion of the particle with a force (viscous drag force) that is proportional to the instantaneous velocity. In the case of optical trapping inside HC-PCF, the viscous drag force helps to attract and track a particle into the core of the HC-PCF by dissipating the kinetic energy gained by the particle as it falls into the trap's potential energy well. In our study, the fluorescent microspheres are dispersed in water ($\eta = 0.001002$ Pa·s for water at room temperature). The local increase in temperature would result in an increase in kinetic

FIG. 2. (Color online) (a) Picture of sample chamber containing fluid media with fluorescent microspheres sample and HC-PCF. (b) A magnified view of the optical trap reveals the trapping area.

FIG. 3. Sequentially captured images at 3.5 s intervals of time, (a) to (f), showing the movement of two microparticles (solid black and white lines encircling the particle positions are guides to the eyes) to the central core of a HC-PCF by means of an optical trap formed by focusing laser light. Images were cropped to show important features.

energy of the particle, if the particle in the trap is absorbing. Conversely, if the medium itself is absorbing the increase in temperature would result in decrease in local viscosity of the medium. Because the wavelength of the laser beam (800 nm) is within the low absorption region and the particle is not trapped for long, the effect of local heating due to absorption is significantly less.

A broadband light source is employed to view the channel formed in the sample chamber, as shown in Fig. 1. The positioning of the cleaved fiber end is performed by using an XYZ translational stage. The beam coming out of the laser is expanded and collimated and is directed to the back aperture of the trapping objective (L_3) using three mirrors (M_1 , M_2 , and M_3). The beam is expanded for overfilling the back aperture of the trapping objective. The laser power measured before the objective lens is 180 mW. The fiber 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 are

initially attracted laterally and trapped and guided to the core of HC-PCF. Movement of the particle close to the fiber end is imaged through the objective (L_4) onto a CCD camera. Figure 3 shows the sequential images obtained with the camera. Images are taken at 3.5 s intervals.

The fiber containing fluorescent microspheres is removed from the sample chamber and washed externally, using methanol, without disturbing the microsphere inside the core of liquid filled fiber. The presence of the particle inside the central core of the HC-PCF is examined using a microscope and the obtained image is shown in Fig. 4(a). In order to enhance the particle images from the background, the acquired image is filtered by image processing means and the result is shown in Fig. 4(b). The fiber containing the sample is further checked for fluorescent signal using an optical setup. A schematic diagram of the optical setup can be found in Ref. 14. A continuous wave (CW) diode-pumped solid-state (DPSS) 404 nm laser (output power of approximately 5 mW) is coupled into the proximal end of the HC-PCF, immobilized with the

FIG. 4. (a) Microscopic image showing the trapped fluorescent microspheres inside the HC-PCF (imaged with $50\times/0.5$ NA objective lens) and (b) the processed image.

FIG. 5. Fluorescence signal obtained from the HC-PCF at 404 nm excitation.

fluorescence sample, using a high precision single mode fiber coupling (FC) unit (Melles Griot Pte Ltd). The beam emerging from the distant end of the fiber is focused to a high quantum efficiency spectrophotometer (Ocean Optics, QE65000) using a microscope objective ($20\times$, 0.65 NA). The spectrometer is coupled to a PC, which displays the spectrum. The obtained spectrum is given in Fig. 5.

A further experiment was performed to show that our experimental platform using HC-PCF also allows for transferring the trapped sample from fiber to a different fluid medium. This was done by translating the optical trap along the length of fiber. The fiber containing the microsphere

sample is positioned as in Fig. 1. The approximate position of the microsphere sample is spotted under white light illumination with the imaging objective lens (L_4 in Fig. 1(a)). Now the laser beam is switched on and the translational motion along the axis of the fiber is achieved by manually translating the sample chamber stage. The movement is monitored throughout using the CCD camera. The particle comes out of the fiber holes to the liquid medium due to the laser induced optical force. The sequence of images of the particle coming to the medium, shown in Fig. 6, is taken at intervals of 1 s.

In our traverse optical trapping experiment using HC-PCF, fluorescent microspheres dispersed in water were employed as the sample with which the optical manipulation and detection studies were performed. Such dielectric spheres can serve as first simple models of living cells in biological trapping experiments and also as basic particles in physical trapping experiments. In typical biophysical experiments, a polystyrene bead chemically attached to the biomolecule or cell under study is optically trapped, and the analysis of its dynamics allows one to gain insights into the mechanics of the object it is attached with.^{20,21} Appropriate modification of our developed system/concept can lead to optical trapping application of biological objects, including cells, which are also in our near-future research interests. The trapping force acting on a biological cell is much smaller than that of polystyrene beads (refractive index, $n \approx 1.59$) due to the lower average refractive index of cells ($n \approx 1.36$ – 1.4). This relative reduction in total force can be overcome by

FIG. 6. Sequential images (1 s intervals), (a) to (f), showing the movement of a microsphere from the central core to the liquid medium by translating an optical trap along the length of the fiber (white arrow shows the direction of fiber movement and white line encircling the particle position are guides to the eyes). Images were cropped to show important features.

using more light to create a stronger trap; but it should be noted that the increase in light intensity may damage the cell. Also, the cell shape may deviate from a perfect sphere, which can also reduce trap stiffness. The modulations in amplitude and phase of trapping light will allow trapping low-index particles or cells with improved trap stiffness for the future experiments.²²

IV. CONCLUSIONS

A novel optical manipulation and detection method is proposed and illustrated in this paper by combining an optical trap methodology, HC-PCF, and detection techniques. This proposed methodology is particularly advantageous in situations where the sample volume is very low and/or the sample environment is to be frequently changed. Micron sized particles loaded into the hollow core by optical trapping methods can be maneuvered by translating the trap along the length of the HC-PCF. The particle is subjected to multiple characterizations such as imaging and fluorescence signature characterization. The liquid-filled HC-PCF is washed externally without disturbing the sample trapped inside the core and subsequently moved to a different medium by translating the trap along the length of the HC-PCF. The proposed methodology with the miniature size offers a disposable, sterile, and highly sensitive platform for detection and separation of cell like particles in a very low sample volume. This is expected to find potential translational medicine applications in the near future.

ACKNOWLEDGMENTS

The authors acknowledge the financial support received through AcRF. One of the authors, V. K. Shinoj, would also

like to acknowledge Nanyang Technological University for the research student support.

- ¹C. Dongre, J. van Weerd, G. A. J. Besselink, R. M. Vazquez, R. Osellame, G. Cerullo, R. van Weeghel, H. H. van den Vlekert, H. J. W. M. Hoekstra, and M. Pollnau, *Lab Chip* **11**(4), 679 (2011).
- ²M. Hu, J. Yan, Y. He, H. Lu, L. Weng, S. Song, C. Fan, and L. Wang, *ACS Nano* **4**(1), 488 (2009).
- ³J. Van Mameren, E. J. G. Peterman, and G. J. L. Wuite, *Nucleic Acids Res.* **36**(13), 4381 (2008).
- ⁴M. A. van Dijk, L. C. Kapitein, J. van Mameren, C. F. Schmidt, and E. J. G. Peterman, *J. Phys. Chem. B* **108**(20), 6479 (2004).
- ⁵A. Manz, N. Graber, and H. M. Widmer, *Sens. Actuators, B* **1**(1–6), 244 (1990).
- ⁶V. Srinivasan, V. K. Pamula, and R. B. Fair, *Lab Chip* **4**(4), 310 (2004).
- ⁷H. Andersson and A. Van den Berg, *Sens. Actuators, B* **92**(3), 315 (2003).
- ⁸S. Weiss, *Science* **283**(5408), 1676 (1999).
- ⁹B. Eggleton, C. Kerbage, P. Westbrook, R. Windeler, and A. Hale, *Opt. Express* **9**(13), 698 (2001).
- ¹⁰R. F. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. S. J. Russell, P. J. Roberts, and D. C. Allan, *Science* **285**(5433), 1537 (1999).
- ¹¹J. B. Jensen, L. H. Pedersen, P. E. Hoiby, L. B. Nielsen, T. P. Hansen, J. R. Folkenberg, J. Riishede, D. Noordegraaf, K. Nielsen, and A. Carlsen, *Opt. Lett.* **29**(17), 1974 (2004).
- ¹²L. Rindorf, P. E. Høiby, J. B. Jensen, L. H. Pedersen, O. Bang, and O. Geschke, *Anal. Bioanal. Chem.* **385**(8), 1370 (2006).
- ¹³S. Smolka, *Opt. Exp.* **15**(20), 12783 (2007).
- ¹⁴S. Padmanabhan, V. K. Shinoj, V. M. Murukeshan, and P. Padmanabhan, *J. Biomed. Opt.* **15**, 017005 (2010).
- ¹⁵S. Mandal and D. Erickson, *Appl. Phys. Lett.* **90**, 184103 (2007).
- ¹⁶V. K. Shinoj and V. M. Murukeshan, *Opt. Photonics J.* **1**(2), 85 (2011).
- ¹⁷A. Ashkin, *Phys. Rev. Lett.* **24**(4), 156 (1970).
- ¹⁸A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, *Opt. Lett.* **11**(5), 288 (1986).
- ¹⁹K. C. Neuman and S. M. Block, *Rev. Sci. Instrum.* **75**, 2787 (2004).
- ²⁰K. Visscher, M. J. Schnitzer, and S. M. Block, *Nature (London)* **400**, 184 (1999).
- ²¹Z. Bryant, M. D. Stone, J. Gore, S. B. Smith, N. R. Corrazzelli, and C. Bustamante, *Nature (London)* **424**, 338 (2003).
- ²²K. Dholakia and T. Čížmár, *Nature Photonics*, **5**(6), 335 (2011).