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Physics Procedia

ICOPEN2011

Numerical study on Transverse Optical Trapping Inside Hollow-core PCF

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Abstract

In this study, a detailed numerical simulation is carried out to investigate the transverse optical trapping in a water-filled microstructured hollow-core photonic crystal fiber (HC-PCF). Using the FDTD method and Maxwell's stress tensor, the forces acting on the sphere placed at the centre core of HC-PCF is computed. The nature of the force at relative positions of the sphere is also studied. The obtained results indicate that these proposed concepts have significant potential for developing novel optical manipulation and trapping concepts inside such HC-PCF.

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Keywords: Hollow-core photonic crystal fibers; optical trap; Numerical study; FDTD.

1. Introduction

The hollow-core PCFs (HC-PCFs), comprising of an air core with a cladding of two-dimensional (2-D) periodic array of air inclusions in silica, has been widely used as biosensors due to their unique light guidance property in air and the high light-matter interaction obtainable in the central air core [1-3]. The option for placing micro/nano sized particle inside the central air core opens a way of using this fiber in the field of optical manipulation inside the core of hollow-core photonic crystal fiber (HC-PCF). Among the various optical manipulation techniques, optical tweezers or optical trapping methods have attained tremendous interest in the scientific community [4, 5].

In an optical trapping experiment, a laser beam can provide a finite force ≈ pico-Newton, which can trap particles of a wide range of sizes ranging from about 50 nm to 20 μm [6]. Since the invention of using optical force for micromanipulation, several groups have discussed different ways to determine optical force exerted on micro/nano structures. An extended Mie theory was used to study the optical forces acting on small silver nanoparticle aggregates excited at surface plasmon resonance wavelength [7]. Lorentz force law of classical electrodynamics is considered to study the optical force of electromagnetic radiation on isotropic solid media [8]. In this paper, we

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doi:10.1016/j.phpro.2011.06.175

analyze numerically the optical force exerted on the particle located inside the central core of HC-PCF using Maxwell stress tensor and finite difference time domain (FDTD) method.

2. Numerical Geometry

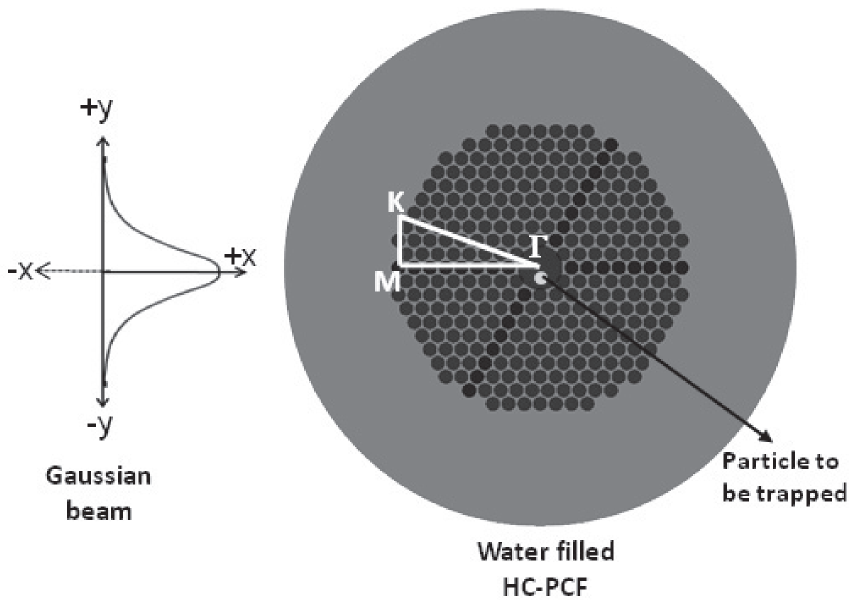

Figure 1: Schematic of the configuration considered for trapping inside hollow-core of HC-PCF

Figure 1 shows the schematic diagram of the configuration considered for the proposed simulation study of trapping across a HC-PCF. The two-dimensional FDTD (2D FDTD) method [9] employed in this study uses perfectly matched boundary layers to simulate the propagation of the optical trapping beam across the PCF. Since the PCF is much longer in the longitudinal direction than in the transverse, we can consider it as a 2D planar structure, neglecting the out of the plane beam divergence. The fiber we have considered here is an HC-PCF designed for air-filled operation at 1550 nm. The hollow core has a diameter of 10.9 µm surrounded by a microstructure comprised of eight periods of hexagonally packed cylinders with a period of 3.8µm and a filling fraction of around 90%. The silica of the fiber has a refractive index of 1.45 and the fiber is filled with distilled water (n=1.33). The external diameter of the HC-PCF is 125 µm. The particle considered is polystyrene (n = 1.59) sphere of radius 0.05 µm, and is trapped in water by a Gaussian beam of waist width 0.8 µm and free space wavelength 980nm. The optical trapping beam launched into the system using a 0.7 NA thin lens. The wavelength used is outside the transverse partial bandgap which is necessary for the trapping using HC-PCF. The trapping beam is injecting in the +x direction.

A grid size of 70 µm × 20 µm is chosen as the overall simulation area, where a small region 1.2 µm × 1.2 µm surrounds the central region of the core (0, 0). This small region is having grid sizes of 10 nm along x- and y-directions. The larger mesh is chosen everywhere else to help minimize computation time. A total of 14400 (120 × 120) mesh points are used in the computation domain, with 4 perfectly matched layer (PML) cells on each side of the boundary. The PML layer allows the reflected light to escape the simulation volume. In order to record the resultant field on the surface of the sphere, we use a box of power monitors (four 1D monitors) which forms a closed surface to the sphere in 2D FDTD analysis method. The four analysis script located inside the group has been used to obtain the field data. Once the fields across the surface of the particle are calculated for each propagation direction, the entire field at an arbitrary point in the space is given by a superposition of the plane wave response times the appropriate amplitude coefficient. Transverse electric (TE) and transverse magnetic (TM) field components are extracted from the four simulation monitors surrounding the sphere. The force components on a surface is obtained by integrating the dot product of the outwardly directed normal unit vector with the TE and TM components on the corresponding surface followed by the vector addition of those. The force components along the propagation direction are added and are normalized to source power to obtain the F_{ax} (X-component, axial force). Similarly, the transverse force F_{tr} (Y-component, transverse force) can be obtained from the force components in the Y-direction. The 'axial' and 'transverse' directions referred here are relative to the lens axis.

3. Results and Discussion

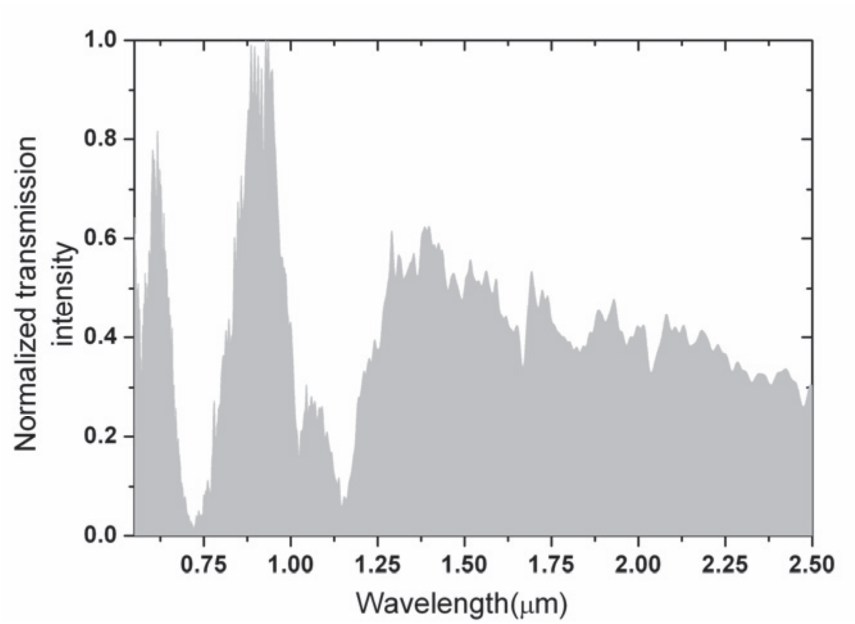

Figure 2: Transmission spectrum obtained at the central core of HC-PCF which is probed transversely by a CW broadband light source with Gaussian profile

HC-PCF can be considered as a 2D photonic crystal for illumination in the transverse direction. Initially, the computational domain is excited by a continuous-wave source with a Gaussian beam profile. The geometry of the HC-PCF is designed such that the trapping beam is propagated in the Γ-M direction. The frequency domain power monitor is used to get the transmission characteristics along the propagation directions. Transmission spectrum is obtained by varying free-space wavelength of the source between 0.55μm and 2.5μm is normalized and presented in figure 2. It is clear from the intensity distribution that partial bandgaps exist in the transverse direction. The simulation predicts a fundamental gap near 2.48 μm and the second order near 1.2 μm. Based on the obtained result, laser with wavelength 940 nm has been selected which is outside the partial bandgaps for further numerical studies on trapping a particle inside HC-PCF. The primary objective is to find out the electro-magnetic field distribution along the surface of the sphere rigorously. A thin lens with NA of 0.7 was used to focus the Gaussian beam, of waist width 3 μm, to the central core of the fiber. By changing the focal point of the beam, the particle is expected to be trapped at the (0, 0) position. The light entering the medium refracts through and reflect off the polystyrene sphere. The changes in photonic momentum cause a resultant force on the sphere. The analytical approach used here is to decompose the illuminating beam into a plane wave spectrum and determine the field distribution for all illumination directions separately where the force is calculated at various positions relative to the waist of the trapping beam. Once the field around the sphere is determined, the next step is to find out the field induced forces acting on the sphere.

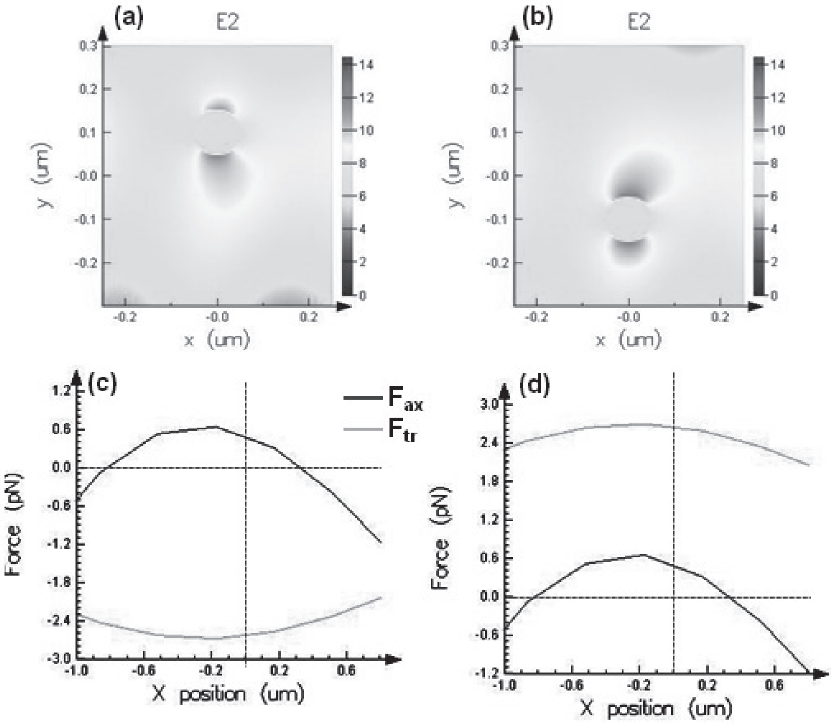

Figure 3: Trapping field distribution ((a) & (b)) and variation of force with axial distance ((c) & (d)) inside the HC-PCF when the sphere is located at (0,100 nm) & (0,-100 nm) respectively.

The field profile at the centre core nearest to the (0, 0) region and the corresponding induced forces are simulated with varied sphere position as well as in the absence of sphere. Fig. 3(a) & 3(c) corresponds to the respective field distribution and the nature of the force when the sphere is located at (0, 100 nm). Fig. 3(b) and Fig. 3(d) represents the field and the corresponding force distribution in the case where sphere position is at (0, -100 nm). The particle being trapped in the x-direction requires the axial force, F_{ax}, to be restorative (to keep the particle at the x=0 point) and its direction is to be opposite to the beam direction. This demands the F_{ax} should have a negative slope region and should go to zero in this region. This ensures that the sphere will be trapped in the x-direction. For the particle located at the positive Y-axis, a negative transverse force, F_{tr}, is induced that will push the particle in the negative y direction towards y=0, where F_{tr}=0. Hence the particle is stably trapped at the point (0, 0). Similarly for the particle located at the negative Y-axis, the condition for a stable trap can be depicted in Fig. 3(d). i.e., F_{ax} has to be restorative with zero value obtained in the negative slop region and the transverse force F_{tr} should be positive ($F_{tr} > 0$) at x=0. Since F_{tr} is positive, the particle will be pushed in the positive y direction towards y=0, where F_{tr} = 0. So the particle will be trapped in the position (0, 0).

Now let us consider the case when the particle is located at (0, 0) and the corresponding field distribution and the nature of force in the central core is shown in Fig. 4(a) and Fig. 4(c) respectively. By the symmetry of the source in the y-direction, the forces normal to the y-axis will cancel each other out at y=0 (i.e. F_{tr}=0). This leaves a restorative axial force in the x-direction. Fig. 4(b) is the field distribution and Fig. 4(d) is the corresponding induced forces in the absence of sphere. In the absence of the sphere, there is negligible field around the focal point of the beam (x=0, y=0) when compared to the field distribution in the presence of the sphere. Theoretically, in the absence of sphere, the force should be zero. The discrepancy here could be due to numerical errors. When compared to the obtained force values in the presence of the sphere, the corresponding values obtained in absence of the sphere are negligibly small.

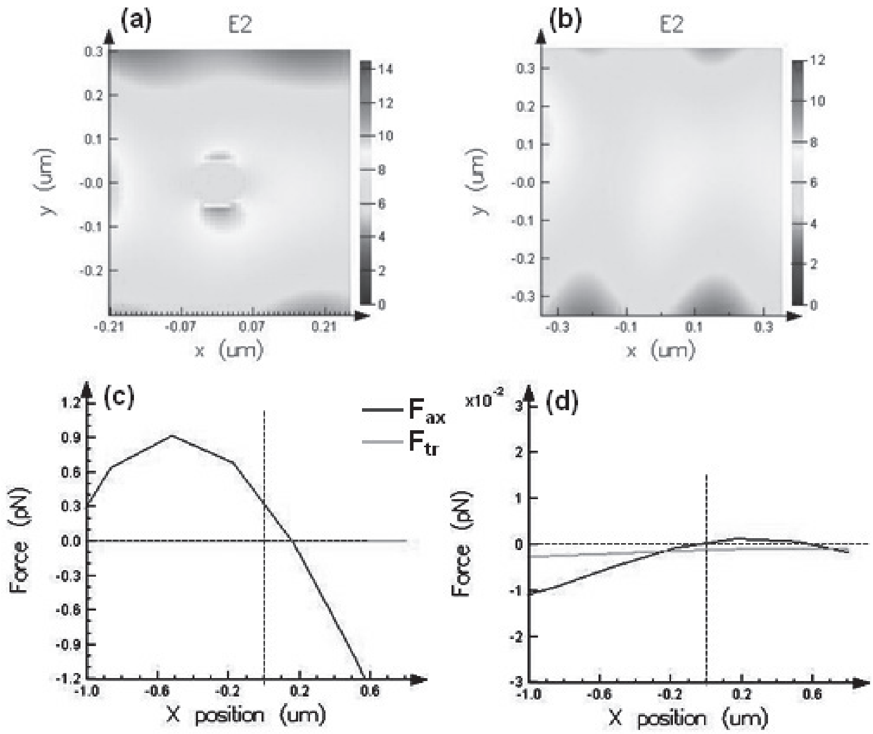

Figure 4: Trapping field distribution ((a) & (b)) and variation of force with axial distance ((c) & (d)) inside the HC-PCF when the sphere is located at (0,0) & in the absence of the sphere respectively.

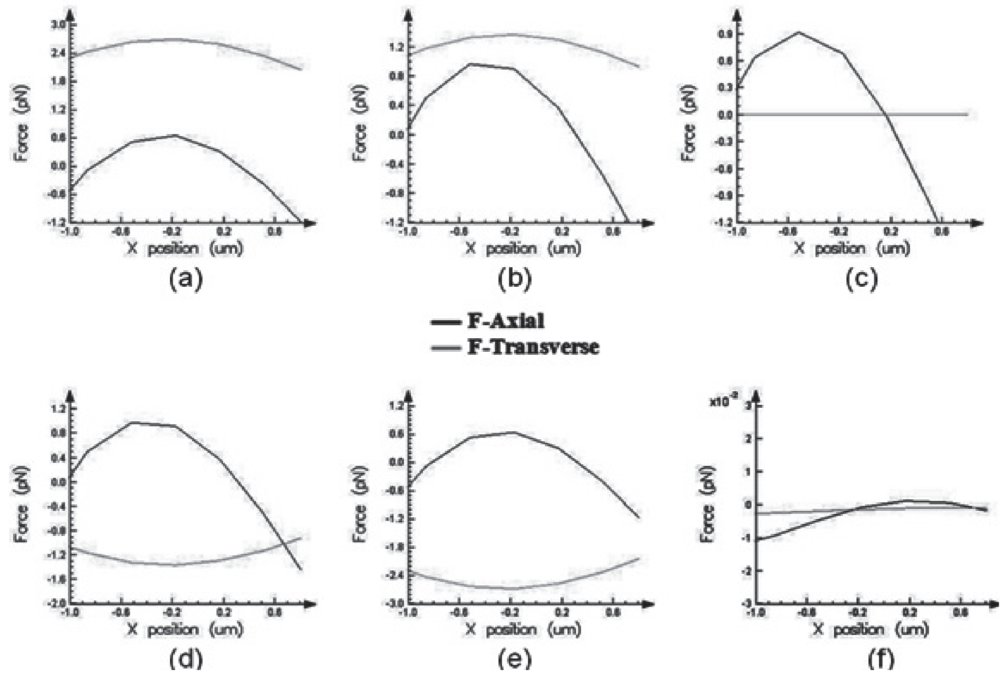

Figure 5: Variation of force with axial distance (a) when the sphere is located (a) at (0, -100nm), (b) at (0, -50nm), (c) at (0, 0), (d) at (0, 100nm), (e) at (0, 50nm) and (f) in the absence of sphere.

The nature of axial and transverse forces around the central core region (0, 0) is estimated at various sphere positions. A close look at the behaviour of the force at various sphere positions corresponding to (a) (0, -100nm), (b) (0,-50nm), (c) (0, 0), (d) (0,100nm) and (e) (0,50nm) is given in figure 5. The restorative axial force induced by trapping beam, which is directed opposite to the beam direction, always tries to keep the particle at the x=0 point. The axial force hence should have a negative slope region and should go to zero in this region as shown in figure 7. For the particle located at the negative Y-axis, a positive transverse force tries to keep the particle stably at the point (0, 0) (figure 5(a) & (b)). Similarly for the particle located at the positive Y-axis, the transverse force should be negative and it is observed in figure 5(d) & (e). The magnitude of this transverse force is higher for the particle located farther from the origin (either positive or negative Y-axis) and it is clear from figure 5(a), (b), (d) and (e). In the case when the particle is located at Y=0, only a restorative axial force is needed to keep the particle at (0, 0) (figure 5(c)). Figure 5(f) corresponds to the situation where the sphere is absent.

4. Conclusion

It is illustrated through 2D FDTD simulation that by employing an external beam focused transversely through the side of an HC-PCF, it is possible to optically trap small sized particle inside its hollow-core. We have carried out a detailed analysis on the nature of the acting forces with respect to the relative positions of the particle inside the hollow-core. Wavelength of the trapping beam is selected such that it is outside the transverse partial bandgaps obtained from the transmission spectrum of the HC-PCF under consideration. The rigorous diffraction theory used to calculate force acting on the sphere involved two steps. In the initial step, the diffraction problem is solved and the field around the particle is calculated. In the second step, the force acting on the particle is computed by applying Maxwell's stress tensor. The results indicate that the central hollow-core can be used as an efficient trapping medium. This proposed approach and concepts can lead to the development of a new type of optical manipulation technique for the nano/micro sized particles/cells which can find potential applications in microfluidics and cell sorting.

Acknowledgment
We thank the Optics and Photonics Society of Singapore and the Nanyang Technological University (NTU) for their support. The authors thank ARC 3/08 (MOE) for the financial support. One of the authors, V K Shinoj, thanks NTU for the research scholarship award.

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