



Reconfigurable Optothermal Microparticle Trap in Air-Filled Hollow-Core Photonic Crystal Fiber

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(Received 3 May 2012; published 9 July 2012)

We report a novel optothermal trapping mechanism that occurs in air-filled hollow-core photonic crystal fiber. In the confined environment of the core, the motion of a laser-guided particle is strongly influenced by the thermal-gradient-driven flow of air along the core surface. Known as “thermal creep flow,” this can be induced either statically by local heating, or dynamically by the absorption (at a black mark placed on the fiber surface) of light scattered by the moving particle. The optothermal force on the particle, which can be accurately measured in hollow-core fiber by balancing it against the radiation forces, turns out to exceed the conventional thermophoretic force by 2 orders of magnitude. The system makes it possible to measure pN-scale forces accurately and to explore thermally driven flow in micron-scale structures.

DOI: 10.1103/PhysRevLett.109.024502

PACS numbers: 47.15.G–, 87.80.Cc

Introduction.—Radiation pressure from focused laser beams has been used to control the motion of micrometer-sized particles [1], permitting contact-free measurements of pN-scale forces on trapped microparticles [2,3], transportation of particles along waveguides [4–8], and optical micromanipulation [9,10]. Thermal forces, caused by optical absorption, can also be used to manipulate microparticles [11]. For example, absorption of light can cause a nonuniform temperature distribution across a particle so that molecules leaving a warm particle surface gain more momentum than those in colder regions. The resulting photophoretic force can be used to trap and transport particles over extended distances in air [12]. Another type of force is related to “thermal creep flow” (TCF), itself caused by temperature gradients along solid-fluid interfaces [13]. TCF has been used to create a Knudsen vacuum pump in a narrow gas-filled capillary [14]. In the case of particles immersed in fluids, TCF at the particle surface causes a thermophoretic force [15] that can be used to trap and concentrate DNA as well as microparticles [16,17].

Hollow-core photonic crystal fiber (HC-PCF) [18] allows dielectric particles to be optically trapped at the center of the fiber core while being laser-propelled along the fiber axis by radiation pressure. We recently measured small external forces on particles guided in both liquid-filled [19,20] and air-filled HC-PCFs [21] by balancing them against the radiation pressure provided by the waveguide mode. In this Letter we demonstrate that, within the confines of an air-filled HC-PCF, the viscous drag force on particles, caused by micron-scale TCF at the core walls, can exceed the thermophoretic force by several orders of magnitude. Unlike in photophoretic experiments, the temperature gradient is created along the fiber rather than across the particle, enabling optothermal manipulation of nonabsorbing particles. We measure the effects of both a static temperature gradient and a dynamic temperature

distribution created by absorption of light scattered by the particle itself. The dynamic response of this novel optothermally coupled system is confirmed by numerical modeling. HC-PCF provides a unique micro-environment for accurate fundamental studies of pN-level optical and thermal forces on the micron scale.

Experimental setup.—A schematic of the setup is shown in Fig. 1(a). The photonic band gap HC-PCF [Fig. 1(d)] shows fundamental mode guidance [Fig. 1(b)] with transmission losses below 0.2 dB/m in the 970–1070 nm wavelength range. The low optical attenuation means that the radiation pressure along the fiber is highly uniform, allowing a particle to be laser-propelled with constant force over meter-long distances [21]. Before selectively launching a silica microparticle (Kisker Biotech PSi-5.0) into the HC-PCF, it is first held at the core entrance using a dual-beam trap consisting of two counter-propagating fiber modes [21]. While in this position the particle radius is measured using a microscope. Thermal forces are introduced by

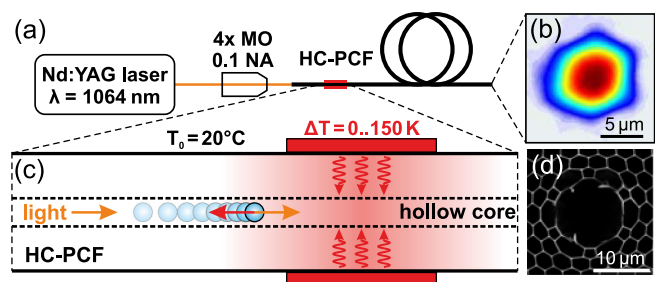


FIG. 1 (color online). (a) Optical setup: MO—microscope objective; NA—numerical aperture; YAG—yttrium aluminum garnet. (b) Measured near-field intensity. (c) Schematic of how fiber heating causes speed variations of the microparticle in the heated region. Heating element is not drawn to scale (it is ~ 50 times longer than the outer fiber diameter). (d) Scanning electron micrograph of HC-PCF structure, core radius $R = 6 \mu\text{m}$.

heating a 1.2 cm long section of the HC-PCF, 40 cm distant from the core entrance, using a cylindrical heating element [Fig. 1(c)]. The resulting static temperature distribution is uniform within the heated zone and falls off on either side, as confirmed by finite element modeling (see Supplemental Material [22]).

Propulsion through heated region.—In the first experiment, a particle of radius $a = 3.2 \mu\text{m}$ was optically propelled through the heated region at an optical power of 72 mW. Its velocity u was monitored by in-fiber laser Doppler velocimetry [23]. The resulting velocity traces in Fig. 2(b) reveal two important effects that both depend on the temperature difference ΔT between the heating device and the surroundings. First, within the heated region the particle moves at constant but reduced velocity. This effect is caused by the increase of the air viscosity with temperature. Second, the particle velocity significantly drops just before it reaches the heated region. The minimum velocity is obtained at a position close to the heating element, and the velocity reduction increases with ΔT . After passing the heated region, the particle recovers its initial velocity. The conclusion is that the force slowing the particle down is driven by the static temperature gradient near the edges of the heating element. Indeed, a reference measurement with a switched-off heating element [Fig. 2(b), $\Delta T = 0 \text{ K}$] showed only small random speed fluctuations of $\sim 5\%$ all along the fiber, probably caused by intermodal beating

between the fundamental fiber mode and a weakly excited higher order mode [23].

Interestingly, above a threshold temperature difference ΔT_{TH} the particle comes to a halt in front of the heating device [Fig. 2(b)]. In this situation, the optical and thermal forces are precisely balanced. ΔT_{TH} is measured by slowly reducing the temperature of the heater while keeping the optical power constant, until the particle resumes its motion. The measurements were repeated for a range of optical powers and show that ΔT_{TH} is linearly proportional to the laser power [see Fig. 2(c)]. The radiation pressure on the particle F_{opt} is estimated using a ray-optics approach [24], approximating the intensity distribution across the core by that of the fundamental EH_{11} mode of a hollow circular waveguide [25]. The accuracy of this approach has been demonstrated in a previous study [21]. From the calculated optical force we conclude that the thermal force is proportional to the threshold temperature difference, i.e., $F_{\text{th}}/\Delta T_{\text{TH}} = 0.38 \text{ pN/K}$.

Thermal forces.—Close to any gas-solid boundary, in the presence of a temperature gradient $\partial T/\partial z$ in the gas along the interface, TCF causes an average movement of gas molecules towards warmer regions [13], yielding a flow velocity at the boundary of [11]:

$$V_{\text{TCF}} = \frac{\eta R_s}{p(1 + 4\text{Kn})} \frac{\partial T}{\partial z}, \quad (1)$$

where p is the air pressure, R_s the specific gas constant, η the viscosity of air, and $\text{Kn} = \Lambda/R$ the Knudsen number where Λ is the mean free path of the molecules (in our case $\text{Kn} \sim 0.01$). The temperature distribution $T(z)$ along the fiber can be estimated by finite element modeling [22], assuming, for instance, a constant heating element temperature of $\Delta T = 120 \text{ K}$. The resulting temperature gradient in the core attains a maximum value of $\partial T/\partial z \sim 0.2 \text{ K}/\mu\text{m}$ near the edge of the heating element.

We now consider two possible mechanisms that could explain the observed thermal force: TCF at the surface of the particle (this is known as thermophoresis), or TCF at the core walls. The thermophoretic force on the particle can be written [11]:

$$F_{\text{TP}} = -\frac{12\pi\eta^2\kappa a R_s}{p(1 + 2\kappa)} \frac{\partial T}{\partial z}, \quad (2)$$

for low Knudsen numbers ($\text{Kn} \ll 1$), where $\kappa = 0.02$ is the ratio between the thermal conductivities of air and silica. For a temperature gradient of $0.2 \text{ K}/\mu\text{m}$ this results in $F_{\text{TP}} = 0.5 \text{ pN}$ (assuming $p = 1013 \text{ mbar}$, $\eta = 18 \mu\text{Pa}$, $R_s = 287 \text{ J kg}^{-1} \text{ K}^{-1}$), which is 2 orders of magnitude lower than the experimentally measured thermal force of 45 pN at $\Delta T = 120 \text{ K}$ in Fig. 2(c), showing that thermophoretic forces do not play a significant role in the PCF system.

Close to the inner surfaces of the air-filled PCF core, TCF pushes gas molecules towards the hotter regions,

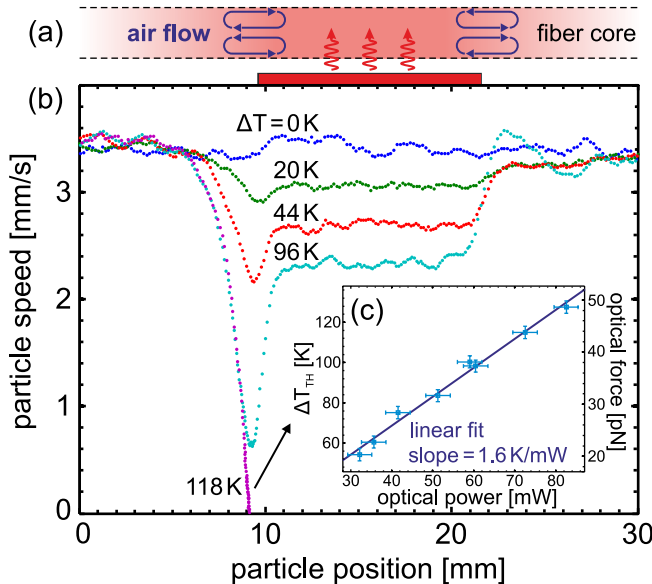


FIG. 2 (color online). (a) Schematic of thermally induced air flow pattern in the hollow PCF core. (b) Doppler velocimetry trace of an $a = 3.2 \mu\text{m}$ particle moving through the heating element (position indicated on top) at an optical drive power of 72 mW. (c) Threshold temperature difference ΔT_{TH} , above which the particle is unable to pass through the heated region, as a function of optical power. The right-hand axis shows the calculated axial component of the optical force (slope = 0.6 pN/mW).

creating a pressure gradient along the fiber core, the highest pressure occurring at the center of the heating element. As depicted schematically in Fig. 2(a), this drives a return flow of gas along the center of the core. In the laminar flow regime ($Re < 0.01$ in the fiber core) for low Knudsen numbers, the steady-state flow velocity profile across the core is expected to be parabolic [26]. Given that the net mass flow of gas in the core is zero, it can be shown by integrating across the core that the flow velocity will equal $+V_{TCF}$ at the core wall and $-V_{TCF}$ at the core center. Using a frame of reference that shifts at velocity $+V_{TCF}$, the resulting viscous drag force acting on a stationary particle placed at the center of the core can be shown to be:

$$\begin{aligned} F_{TCF} &= -6\pi\eta a(K_1 u^* - K_2 V^*) \\ &= -6\pi\eta a(2K_2 - K_1)V_{TCF}, \end{aligned} \quad (3)$$

where $V^* = -2V_{TCF}$ is the center-channel fluid velocity and $u^* = -V_{TCF}$ the particle speed in the moving frame, $K_1(a/R)$ is the wall-correction factor for ($|u^*| > 0$, $V^* = 0$) and $K_2(a/R)$ the factor for ($u^* = 0$, $|V^*| > 0$) [27]. Without freely adjustable parameters, and for the same temperature gradient, we obtain a thermal creep force $F_{TCF} = 50$ pN from Eq. (3), in reasonable agreement with the experimentally measured value of 45 pN at $\Delta T = 120$ K in Fig. 2(c). These results confirm that viscous drag induced by TCF dominates over conventional thermophoretic forces in HC-PCF.

Particle dynamics.—We now study the dynamics in the case when a particle is optically propelled towards a short section of fiber that is externally coated with an absorbing material (made with a black marker pen). As the particle approaches the black mark, forward-scattered light is absorbed by the mark, causing local heating of the fiber [Fig. 3(a)]. In the experiment, an $a = 3$ μm particle was propelled at an optical power of 50 mW towards a ~ 0.5 mm long mark. The particle trajectory was visualized via its side-scattered light and shown in Fig. 3(b). Far from the mark the particle velocity is constant, but it starts abruptly to slow down ~ 200 μm before the black mark and is then repelled backwards, reaching a rest position after ~ 0.2 s. The optothermal trapping position is highly reproducible and stable over time, moving by only a few μm when the optical power is varied from 30 to 200 mW. Since radiation pressure is proportional to laser power, we conclude that the thermal creep force must also scale linearly with power.

The equation of motion for an on-axis particle laser-guided along a HC-PCF in the presence of a thermal creep force F_{TCF} is given by:

$$\begin{aligned} m\dot{u}(t) + 6\pi K_1 a \eta(t) u(t) \\ = F_{\text{opt}} - \frac{6\pi(2K_2 - K_1) a R_S \eta^2(t)}{p(1 + 4Kn)} \frac{\partial T(t)}{\partial z}, \end{aligned} \quad (4)$$

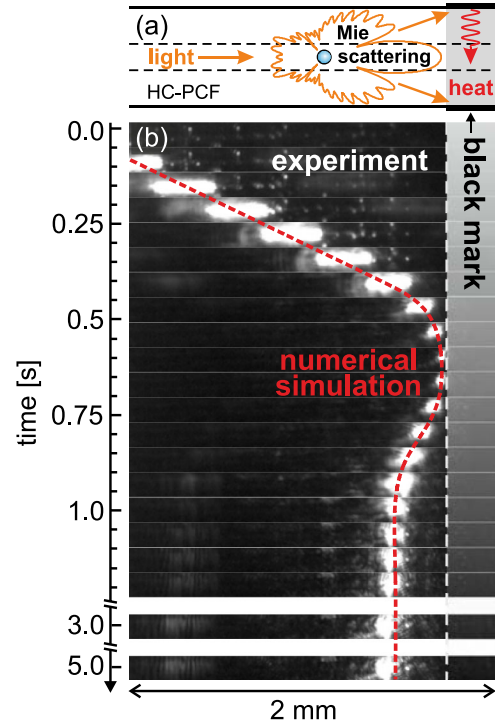


FIG. 3 (color online). (a) Schematic and (b) movie image sequence of an $a = 3$ μm particle propelled along the fiber by 50 mW of laser power (MOVIE 1 in Supplemental Material [22]). It stops abruptly when approaching the black mark (length 0.5 mm). The dashed red curve indicates the numerically computed trajectory.

where m is the mass of the particle. The second term is the Stokes drag force on the moving particle. Since F_{opt} is known (see above) the dynamics of the thermal force can be extracted by monitoring the particle speed u .

The fraction of scattered light absorbed by the black mark is calculated using the angular scattering pattern obtained from Mie theory. The impulse response of the core temperature to the absorbed energy is then numerically computed using the heat transfer module of Comsol Multiphysics. The dynamic temperature distribution $T(t)$ is obtained by integrating the heat impulse response over all former times. A detailed description is provided in the Supplemental Material [22]. The only freely adjustable parameter in the model is the absorption efficiency ε of the absorbing material. The calculated particle trajectory [dashed curve in Fig. 3(b)] turns out to agree well with the experimental data for $\varepsilon = 0.66$, which is close to the value $\varepsilon = 0.63$ obtained from a reference measurement of a black mark on a glass slide.

In the next experiment the thermal force was reduced by marking only the top of the fiber [see Fig. 4(a)]. The smaller black area and the reduced heating allowed the particle to pass through the marked region. Even though the mark is azimuthally asymmetric, modeling confirms that the transverse temperature distribution in the core stays highly uniform, because the transverse heat diffusion

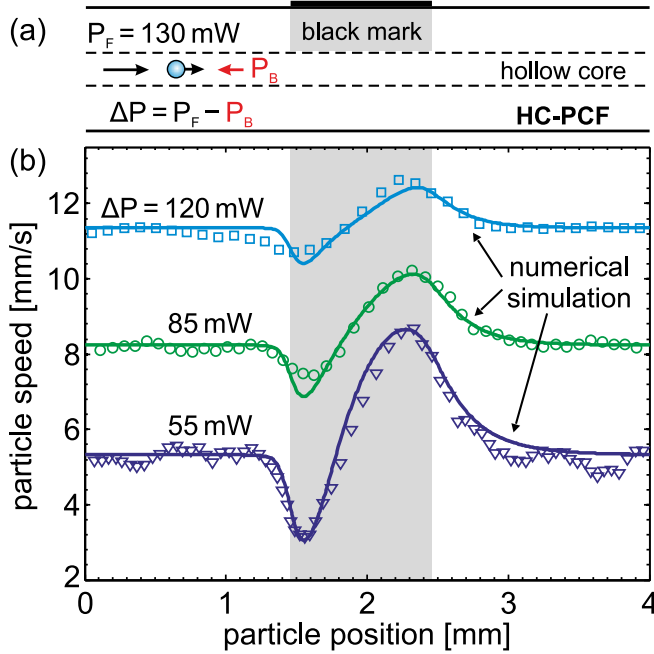


FIG. 4 (color online). (a) Schematic of experimental configuration with counter-propagating beams (wavelength 982 and 1064 nm), power imbalance ΔP . (b) Doppler velocimetry (symbols) and numerical speed traces (lines) of an $a = 3.2 \mu\text{m}$ particle propelled through partially absorbing mark (length 1 mm) at three values of ΔP .

time across the air-filled fiber core (several μs) is much shorter than the dwell-time of the particle in the marked region (tens of ms). Transverse thermal forces are therefore neglected in the analysis.

Next, counter-propagating fiber modes were used to propel an $a = 3.2 \mu\text{m}$ particle towards the marked region. The power in the forward propagating mode was kept constant at $P_F = 130 \text{ mW}$, while the power in the backward propagating mode P_B was varied to control the approach speed of the particle. Figure 4(b) shows experimental velocity traces (symbols) for three values of $\Delta P = P_F - P_B$. In all the experiments, the particle is seen to decelerate as it approaches the mark, a velocity minimum being reached just inside the marked region. As the particle moves through the black mark, its velocity increases again, attaining a maximum value before exiting the mark. This asymmetry is caused by the change in sign of $\partial T / \partial z$ across the mark, which reverses the direction of the TCF drag force. Once it has passed the black mark the particle recovers its initial velocity. The amplitude of the velocity variation depends on the approach velocity, a higher value allowing the mark less time to heat up and reducing the effect of the thermal force. The measured speed traces are compared to numerical modeling (solid curves) in Fig. 4(b). Good agreement is found using $\varepsilon = 0.21$ suggesting that approximately one third of the fiber surface was covered with the black mark. The theory also reproduces the amplitude difference between the initial

velocity drop and the velocity increase at exit from the marked region—related to fiber heating during propagation of the particle through the mark.

Conclusions.—Localized light-driven microflows result in an optothermal force that can be used to manipulate the motion of microparticles. The observed TCF force is 2 orders of magnitude larger than conventional thermophoretic forces. The approach, demonstrated here using laser-guided microparticles in HC-PCF, could be readily integrated into lab-on-a-chip devices [28] and complements the currently available techniques for reconfigurable optofluidic particle manipulation [29]. For instance, laser-propelled particles can be kept stationary at an arbitrary position along a waveguide simply by placing a light-absorbing mark up-stream of the desired point. Using resonantly absorbing materials such as plasmonic structures [30], the optothermal effect could be switched on and off by tuning the laser wavelength. Within the absorbing section, such a system would allow us to control the direction of the particle motion using a single laser beam, in a manner similar to recently reported “tractor beams” [31,32]. The HC-PCF system allows very precise measurements to be made of thermal forces acting on small particles in confined geometries (difficult to do any other way) over a wide range of gas pressures, and is likely to be useful for fundamental studies of fluid dynamics.

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