Optical trapping and transportation of carbon nanotubes made easy by decorating with palladium

Manas Khan and A. K. Sood
Department of Physics, Indian Institute of Science, Bangalore - 560012, India
Author for correspondence: asood@physics.iisc.ernet.in

S. K. Mohanty and P. K. Gupta
Biomedical Application Section, Centre for Advanced Technology, Indore - 452013, India

Girish V. Arabale and K. Vijaymohanan
Physical and Materials Chemistry Division, National Chemical Laboratory, Pune - 411008, India

C.N.R. Rao
Chemistry and Physics of Materials Unit, Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore - 560064, India

Abstract: Individual carbon nanotubes being substantially smaller than the wavelength of light, are not much responsive to optical manipulation. Here we demonstrate how decorating single-walled carbon nanotubes with palladium particles makes optical trapping and manipulation easier. Palladium decorated nanotubes (Pd/SWNTs) have higher effective dielectric constant and are trapped at much lower laser power level with greater ease. In addition, we report the transportation of Pd/SWNTs using an asymmetric line trap. Using this method carbon nanotubes can be transported in any desired direction with high transportation speed.

OCIS codes: (140.7010) Trapping; (120.4610) Optical fabrication

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1. Introduction

Recent work on carbon nanotubes has revealed their potential uses in varied fields such as nanoelectronics, electron emitters in flat-panel displays, gas and liquid flow sensors, actuators etc. [1, 2]. Their mechanical, chemical, electrical and optical properties have made them a useful assembly unit for many nano-structured technological devices. It has now, therefore, become necessary to have a control over the arrangement of the nanotubes in desired patterns. Techniques such as single tube manipulation by atomic force microscopy [3, 4, 5, 6], dielectrophoresis [7], and flow-induced alignment [8] have been employed to serve the purpose. Recently, single-wall carbon nanotubes (SWNTs) were trapped using optical tweezers [9, 10] and manipulated using dynamic holographic optical tweezers [9]. Here we report how single-wall carbon nanotubes decorated with Pd nanoparticles (Pd/SWNTs) can ease the optical manipulations at individual nanotube level. This is because of the increase in the effective dielectric constant of the decorated nanotubes. Furthermore, we demonstrate the transportation of Pd/SWNTs using an asymmetric optical line trap [11] that does not require the use of a scanning device [9] or micro fluid channels [10].

2. Experimental details

We have used SWNTs decorated with Pd metal for our experiments and compared the results with pure SWNTs. Pure SWNTs were prepared by the arc discharge method, followed by the purification process to remove the carbonaceous impurities and metal catalyst particles [12]. SWNTs partially covered by Pd were prepared by dispersing 450 mg of carbon nanotubes in 25 ml acetone with the aid of sonicator. 204 mg of $PdCl_2$ was added to the dispersion and sonicated again for 10 minutes. The sample was refluxed to 373 K for 3 hours. After solvent removal the sample was reduced in H_2 atmosphere at 773 K for 2 hours and allowed to cool. Pd/SWNTs were characterized by various techniques and the absence of unreacted $PdCl_2$ in the sample was confirmed. It has been shown that such treatment gives rise to nanotubes decorated with metal nanoparticles [13]. From the TGA studies, the wt% of Pd was calculated as 23%. Ellipsometry studies on the bulk samples were performed using Sentec Ellipsometer (model: SE850) to measure the enhancement in dielectric constant of SWNT after decorating with Pd nanoparticles. It was observed that there was a substantial change in the real part of the dielectric constant, $Re[\varepsilon_{SWNT}] = 1.58$ to $Re[\varepsilon_{Pd/SWNT}] = 1.71$ at 1064 nm. On the other hand, the imaginary part of the dielectric constant which plays an important role in heating of the sample while in the optical trap, was almost same: $Im[\varepsilon_{SWNT}] = 0.85$ as compared to $Im[\varepsilon_{Pd/SWNT}] = 0.87$ at 1064 nm. The SWNT and Pd/SWNT samples were dispersed in 1% $SDS + D_2O$ solution at 20 mg/l concentration and sonicated for more than 10 hours. The SWNT and Pd/SWNT dispersions were centrifuged for 30 minutes at 16000 rpm and only the upper part of the dispersions were taken for the experiments to ensure the absence of nanotube bundles in the samples [14].

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A 1064nm linearly polarized laser beam from a 2.5 W $Nd:YVO_4$ laser was focused through a 1.4 numerical aperture $100\times$ objective to trap the nanotubes. The laser power was increased gradually to measure the threshold laser power to trap the pure SWNTs and the Pd/SWNTs. The experiments were recorded using a digital CCD camera attached to the microscope. As the size of the SWNTs are smaller than the optical microscopy resolution limit, the diffraction limited images of the trapped SWNTs are seen like a blurred dark spot at the trap center (Fig. 1).

For the transportation of the nanotubes, we used an asymmetric optical line trap. The nanotube dispersions used in the transportation experiments were not centrifuged and therefore the samples were not free from small nanotube bundles. Replacing a spherical lens of the telescopic pair outside the microscope by a cylindrical lens makes the laser beam focus only in one direction and hence results in a line trap in the sample plane. A schematic of the optical layout has been shown in Fig. 2. As shown in the Fig. 2, when the laser beam is tilted slightly (about Y axis), the intensity profile as well as the potential well of the line trap become asymmetric [11]. Tilting the laser beam in the other direction allowed us to reverse the asymmetry while the angle of tilt governed the degree of asymmetry in the line trap. We used SWNT and Pd/SWNT dispersions for the transportation experiments at various laser power levels. The transportation experiments were recorded at 25 frames per second using a CCD camera. Due to poor optical contrast and higher speed of transportation, the images of transportation of very small Pd/SWNT bundles are not clear enough. The time lapse images of transportation of a rather big bundle of Pd/SWNT have been shown in Fig. 3.

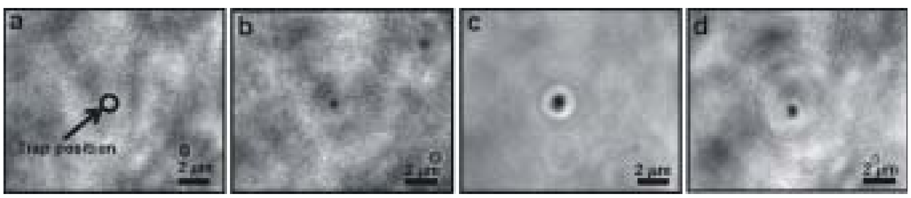

Fig. 1. Optical microscope images of trapped Pd/SWNT (a-c) and pure SWNT (d). In frame (a) the laser is off. Frame (b) shows the trapping of Pd/SWNT at 118 mW laser power. The image is a diffraction limited image and hence it does not represent the real size of the trapped nanotube. In (c), the trapping of SWNT-Pd has been shown at laser power of 170 mW when more than one nanotube get trapped and a more prominent dark spot is visible at the trap center. Frame (d) shows the trapping of pure SWNT at 214 mW.

3. Results

Pd/SWNTs were trapped with relative ease compared to pure SWNTs. We could trap the Pd/SWNTs starting from a threshold value of the laser power of 118 mW. As shown in Fig. 1, a blurred dark spot at the trap center was seen as the signature of the trapping of Pd/SWNTs. With increasing power the dark spot became more prominent as more than one nanotube were trapped. As compared to Pd/SWNTs, the threshold laser power for trapping of pure SWNTs was much higher, 214 mW, and the trapping was not as stable as that of the Pd decorated sample. Even at 214 mW, the trapped SWNTs showed greater thermal agitation and were kicked out of the optical trap in collisions with the new incoming SWNTs, whereas all trapped Pd/SWNTs stayed in the optical trap and did not show any visible thermal agitation till the laser power was decreased below the threshold value of 118 mW.

Pd/SWNTs could be transported using the asymmetric optical line trap whereas this was not the case for pure SWNTs. The Pd/SWNTs were attracted to the potential well from the steeper

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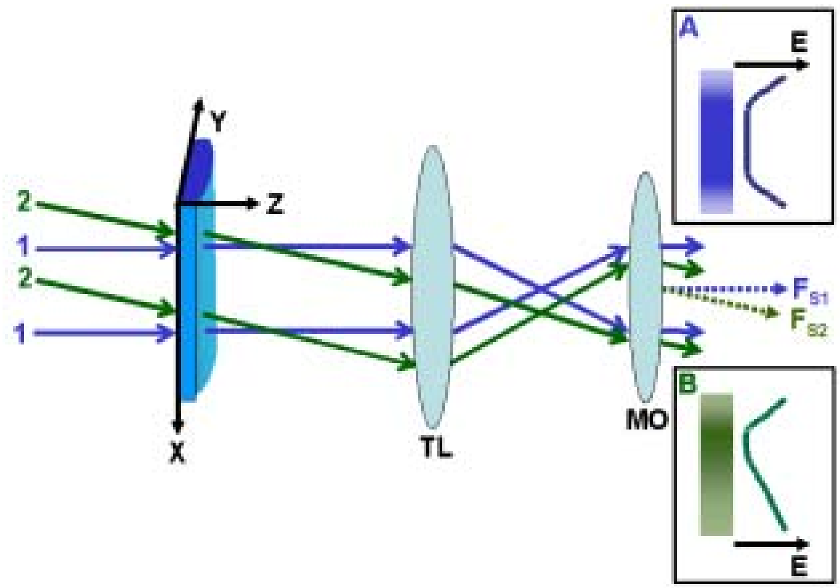

Fig. 2. Optical layout of the asymmetric line trap. For normal incidence (beam position 1) on the cylindrical lens, a symmetric line trap is formed at the sample plane. The intensity profile and the corresponding potential well for this case have been shown in inset A. When the incident beam is tilted about Y axis (position 2), the intensity profile and the potential well of the line trap become asymmetric. The intensity profile and the potential well corresponding to beam position 2 have been displayed in inset B. For beam position 2, the scattering force (F_{S2}) gains a nonzero transverse component acting along the direction of flatter potential of the line trap. TL and MO represent the tube lens and the microscope objective respectively.

intensity gradient side of the line trap with very high velocity and then were pushed to the other end of the line trap with a slower velocity (Fig. 3). The absolute velocity of the transportation increased with increasing laser power. For smaller bundles, the transportation speed as high as 25 $\mu m/sec$ was observed and bundles were transported over a length of 8 μm at laser power of 200 mW. The direction of transportation could be reversed just by tilting the laser beam in the opposite direction (about Y axis) (Fig. 2). The speed of transportation could also be regulated by the tilting angle of the beam. A rotation of the cylindrical lens about the optic axis (Z axis) made the line trap to rotate about the Z axis in the sample plane and using this process all the desired directions of transportation were realized.

4. Discussion

The difficulty in trapping of individual carbon nanotubes is twofold, small size and low dielectric constant. In the strongly focused laser beam a nanotube gets polarized and starts interacting with the strong electric field at that point. The dipole interaction energy can be given by,

$$W = -\alpha \int I dV \qquad (1)$$

where $\alpha = \frac{\varepsilon_p}{\varepsilon_0} - 1$ accounts for the relative difference of the dielectric constants of the nanotube (ε_p) and the surrounding medium (ε_0), I is the electromagnetic energy density [15] which is a sole function of the spatial coordinates for a CW lasr beam and the spatial integral is done

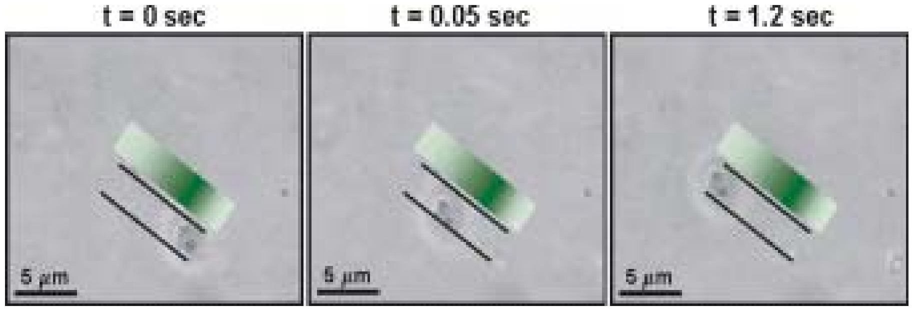

Fig. 3. Time lapse images of the transportation of a Pd/SWNT bundle in the asymmetric line trap. The parallel lines indicate the length and direction of the line trap. A color bar in each image indicates the asymmetry in the beam intensity profile of the trap. The bundle is pulled toward the maximum intensity point from the steeper gradient side with a higher velocity and then pushed to the other end at much lower speed.

over the volume of the nanotube. Since both α and V are small for a individual nanotube, the value of the integral is less and as a result it does not get trapped strongly. When the nanotubes are decorated with Pd nanoparticles, the effective dielectric constant and therefore α increases substantially and hence even an individual Pd/SWNT gets trapped at greater ease and at much lower laser power. In this case, the ratio $\alpha_{Pd/SWNT}/\alpha_{SWNT}$ can be approximately calculated as 2 at 1064 *nm*.

As the Pd decorated SWNTs become more participative in optical manipulation, they get transported by the asymmetric optical line trap unlike the pure SWNTs. When the laser beam is tilted about the Y axis, because of the oblique incidence the intensity profile of the line trap become asymmetric (as shown in inset B of Fig. 2) and the scattering force gains a non zero transverse component (Fig. 2). The Pd/SWNTs are pulled in the potential well from the stiffer gradient side by the gradient force and then are pushed away to the other end of the line trap by the transverse component of the scattering force. Since the width of the line trap in the orthogonal direction is very narrow, the Pd/SWNTs follow the path of the line trap and get transported along a predefined direction. With the increasing laser power, the stiffer side of the potential well become more stiffer and the transverse component of the scattering force increases resulting in a faster transportation. A change in the angle of tilt of the laser beam regulates the asymmetry in the intensity profile and hence the potential well of the line trap which, in turn, is reflected in the speed of transportation. By reversing the tilt of the laser beam, the asymmetry of the line trap as well as the direction of the transverse component of the scattering force is reversed and thus the direction of transportation could be flipped. Along with this, as the direction of transportation can be rotated in the sample plane about the Z axis by rotating the cylindrical lens about the optic axis, any desired transportation of the Pd/SWNTs can be achieved.

5. Conclusions

The significance of this work lies in the fact that by decorating SWNTs with Pd nanoparticles, the efficiency of optical trapping and manipulations of the tiny carbon nanotubes that are much smaller than the wavelength of the trapping beam has been enhanced. The enhancement would be even more at higher wavelengths as an absorption peak of SWNT appears at 1000nm. The transportation process reported here is also very useful as the speed of transportation is much higher and it allows to choose the direction of transportation. The optical manipulations of Pd/SWNT will be useful for making sub-micron structures in different needs of nanotechnol-

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