The mechanical oscillation of a single carbon nanocoil driven by a focused laser beam

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Abstract. We have determined the mechanical properties of a long single carbon nanocoil (ALS-CNC) interacting with a focused laser beam. The mechanical oscillation properties of ALS-CNC in liquid based on the interaction of a CNC with light have been demonstrated. Considering the viscous force of a liquid, ALS-CNC oscillation does not occur by laser irradiation when ALS-CNC is in air. A CNC switch controlled by laser irradiation was realized. The first section in your paper.

1. Introduction

Research on light-matter interactions has focused on its applications in various fields, such as biochemistry, sensing and clinical medicine [1-9].

Optical trapping of nano/micro-particles has been researched for many years in some fields such as biology [13,14]. Recently, photophoretic force, which is called light-driven pulling force, due to thermal effect, has been brought into focus about the light-matter interaction research. The resultant forces of them is discussed to manipulate metal objects [10-12]. Photophoretic forces or optical gradient forces are considered as the main reason of objects moving in most cases, as doing in different works [21,22,23]. However, few works research the resultant force of these two kinds of forces for explaining experiment result.

Carbon nanocoils with a unique helical morphology had excellent physical properties and were expected to be applied as living molecular components and nano-spring etc. [15,16,17,18,19,20].

Recently, carbon nanocoil interactions with light is of significant interest which can realize many novel technologies.

Our previous work showed that micro-bubbles can be generated by laser irradiation on carbon nanocoils thoroughly immersed in water [27] and paraffin microspheres can be driven on carbon nanocoils in air by a focused laser beam [28], which is the result of the conversion of light energy to
heat energy. In addition, Carbon nanocoils manipulated by a focused laser beam has been reported by our research team [29,30]. However, the light used in those technologies must be focused precisely on the CNC body. The laser focal point should not deviate from the CNC body.

In 1969, Ashkin reported that an optical gradient force that is parallel to the direction of the laser beam can be applied to micro-particulates near a focused laser beam.

The index of refraction of an object is higher than that of the surrounding medium. Optical pulling forces is applied to the object. In contrast, the index of refraction of an object is lower than that of the surrounding medium. Optical pushing forces is applied to the object. Chen et al. measured the spring constant of individual CNCs and obtained a value of 0.12 N/m, suggesting that the laser focal point deviated from the CNC body [31,32]. The CNC will be acted upon by an optical gradient force, which provides a good opportunity to research the mechanical properties of a long single carbon nanocoil (ALS-CNC) interacting with a focused laser beam.

In this article, we present the mechanical oscillation properties of ALS-CNC driven by focused laser beam. We also show that the potential applications of the light- CNC interaction which may give some interest phenomenon which is attractive.

2. Experimental details
Carbon nanocoils of average coil diameter from 300 to 600 nm were synthesized by chemical vapour deposition in this experiment[33]. In this experiment, a suspension liquid of $Al_2O_3$ powders was selected as as support materials and spin coated on $SiO_2$ substrate. $Fe_2(SO_4)_3/ SnCl_2$ solution was used as catalyst in this experiment. Then the catalyst solutions were dropped on these substrates. Then the samples was dried at 40 – 50°C for 10 min and calcined at 700°C for 30 min to oxidize the catalysts. Acetylene gas was introduced at 60 sccm to a thermal CVD system at 700°C for 30 min in ambient Ar gas. Finally, CNC aggregation can be acquired as shown in fig. 1.

![Figure 1](image1.png)

Figure 1. (a) SEM of the carbon nanocoils synthesized in this study; (b) The enlarged SEM image of a single carbon nanocoil from CNCs aggregation.

ALS-CNC with a length of 50 um obtained from CNC aggregation is attached to the tip of a copper wire on slide glass [34]. Several drops of deionized water were dropped onto the tip of the copper wire on the slide glass, and thus ALS-CNC could be immersed thoroughly in water at room temperature, as schematically shown in fig. 2. The liquid condition for ALS-CNC was easily achieved due to the wettability and hydrophilicity of the slide glass.
Figure 2. Diagram of the fabrication process of a long single carbon nanocoil thoroughly immersed in water. ALS-CNC with a length of 50um is long enough that it cannot be observed inextenso from the microscopic images of a long carbon nanocoil immersed in water, as shown by the two pictures linked together in fig. 3.

Figure 3. Microscopic image of ALS-CNC immersed in water thoroughly. Single-beam optical tweezers system was applied to work in this study, which was described in detail in our previous work [27]. By controlling the focal distance, the laser beam spot with a 4 um diameter will be generated, which is called an optical trap. An optical trap force between the micro-object and the optical trap exists when a micro-object is in the optical trap. Charge coupled device (CCD) camera system can be used to record the process of a micro-object moving.

3. Results and discussion
With increasing distance from the tip of the copper wire on the slide glass, a clearer mechanical effect of ALS-CNC will be shown when a force is exerted on this CNC. Thus, a laser beam was focused on the position near the tip of ALS-CNC, uninterruptedly, as shown in fig. 4. The red spot (see fig. 4) images the location of the energy centre of laser light.

![Figure 4](image)

Figure 4. The process of ALS-CNC immersed in water with self-oscillations recorded by a CCD system. The red spots indicate the focal point of a laser. Laser power illumination is 4.5uW. (a) to (c) show the upper swing of a CNC; (d) to (f) show the lower swing of a CNC.

Fig. 4 (a) to (f) shows the process of ALS-CNC self-oscillations in liquid under prolonged irradiation on a position near ALS-CNC (the laser power illumination is 4.5uW in this experiment). The pictures from (a) to (f) in fig. 4 are a vibration cycle recorded by a CCD camera. The speed of vibration is very quick, and the time of a vibration cycle is less than one second. The schematic diagram is displayed in fig. 5. Therefore, no micro-bubbles can be produced at the site of laser focus due to the conversion of light energy to heat energy, which is different from the previous experiment result has been report by our team [27]. fig. 4 (a) describes the original position of the CNC untreated with laser irradiation. A laser with an illumination power of 4.5uW is focused on the red spot area near
the CNC in water. In addition, the CNC self-oscillations dies down when the laser energy is zero or the site of laser focus is far from the CNC. The amplitude of the CNC self-oscillations becomes very large when the laser irradiation power increases, which is shown in fig. 6.

Figure 5. Schematic of a self-oscillations of ALS-CNC immersed in water induced by the focused laser.

Figure 6. Effect of laser power on amplitude of CNC vibration. The red spots indicate the position of laser focus. The laser power illuminates on the CNC are 4.5uW (a) and 10.5uW (b).

Since photophoretic forces and the trapping forces of focused laser beam are perpendicular to the laser beam [31], the resultant forces of them cause ALS-CNC has to move close to or far away from the location of laser irradiation. However, CNCs exhibit outstanding flexibility due to their unique helical morphologies. Therefore, there are three forces exerted on the single CNC thoroughly immersed in water, including the trapping force from laser irradiation, the restoration force from the CNC flexibility and the damping force from the liquid (supposing the photophoretic force is ignored [20]). Hence, a long single carbon nanocoil self-oscillation occurs in water by laser irradiation.

Interestingly, laser irradiation does not cause ALS-CNC to oscillate around the end of the CNC in air. From fig. 7, ALS-CNC in air is attracted to the position of laser irradiation, and then, the CNC immediately deviates from the original location of laser irradiation under prolonged laser irradiation, as shown in fig. 7(b). Then, the CNC in the air returns to the original position when the laser energy is zero or the site of laser focus is far away from the CNC. The self-oscillation effect does not occur by laser irradiation when ALS-CNC is in air because the damping force in air is less than that in liquid, causing a difference compared to the CNC immersed in water.

Figure 7. Microscopic images of ALS-CNC treated with laser irradiation: The red spots indicate the position of laser focus. (a) untreated; (b) treated; (c) laser beam is shut off.

If ALS-CNC driven by focused laser beam can be controlled, this kind of contiguous self-oscillation can be used for local liquids stirrer at the nanometer scale in chemistry and medical science. In addition, CNCs have shown excellent electrical conductivity properties. Hayashida et al. shows that the electrical conductivity of CNCs is about100S/em [35]. Hence, achieving a CNC switch controlled by laser irradiation in nanodevices or nano/micro electro-mechanic systems is possible.
4. Conclusion
We have discovered that the mechanical oscillation of a long single carbon nanocoil immersed thoroughly in water can be driven by focused laser beam. The mechanism of oscillation is the combining effect of trapping force from laser irradiation, the restores force from CNC flexibility and the damping force from liquid. In addition, we have found that self-oscillation does not occur by laser irradiation on ALS-CNC in air, and the CNC deflects only under prolonged laser irradiation. Our results clearly show that ALS-CNC in air can be used as an electricity switch controlled by laser irradiation in micro-systems or MEMS. Our work provides a new idea for the optically driven movement of CNCs.

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