The photo-mechanical response characteristics of carbon nanocoil-based cantilever

1 | INTRODUCTION

Due to their natural tiny size, large aspect ratio and excellent mechanical property, 1D nanotubes and nanowires have attracted much attention for their promising applications in micro-actuators, such as micro/nano electro-mechanical systems, motors, and biomimetic robots. Carbon nanocoil (CNC), which has outstanding mechanical, electrical and thermal properties, is a kind of quasi-1D carbon nanofiber with unique helical morphology. The excellent flexible and stretchable properties of CNCs benefit their applications in the fields of strain sensors [1, 2] and biological probes [3]. Because of the large aspect ratio, CNCs have been used as cantilevers for mass sensing [4] and mechanical resonators [5–7]. However, the small size of CNCs reduces the operation efficiency while increasing the possibility of mechanical invasiveness.

Compared to conventional mechanical manipulation, remote actuation is a desirable methodology for the activation of nano-scale actuators under complex or special conditions. With the advantages of good controllability, low power consumption and non-invasion, photo-actuation is one of the most powerful approaches for contactless control of nanoactuators. In recent years, laser has been widely used for characterization, manipulation and assembly of micro/nanowires [8–12]. Some progress, which focuses on the photo-actuation of CNCs, has been made. It is found that CNCs show notable photo-mechanical response under laser irradiation [13, 14]. Our previous work has realized the photo-induced vibration of CNC cantilever [15]. In addition, CNC is a good backing material for nanocomposites due to its large specific area. Photo-driven nanocomposites based on CNC/TiO₂ and CNC/VO₂ with multi-motion modes have been developed for photocatalytic nanomotors and infrared micro-detectors, respectively [16–18].

Although considerable progress is achieved, there are some problems restricting the applications of CNC-based photo-actuators. The preparation of CNC-based nanocomposites is expensive and time-consuming, while the small photo-induced amplitude of pure CNC is small. Due to the small optical force (in the scale of 10⁻¹¹ N), the amplitude-to-length ratio of pure CNC cantilever is approximately 0.05 [15], which cannot meet the actual needs. Specifically, the mechanism of light-CNC interaction is still not clear.

FIGURE 1 (a) Optical image of a single CNC cantilever. (b) SEM image of a single CNC cantilever

In this paper, the static photo-mechanical response characteristics and dynamic photo-induced vibration of CNC are investigated. It is found that the photo-mechanical behaviour of CNC is not only attributed to the optical pressure, but also affected by the photothermal coupling between CNC and surrounding environments, which comes from the excellent photothermal ability of CNCs. Moreover, for a curving CNC, through regulating the irradiation point from free end to the fixed end, the vibration amplitude of CNC cantilever increases approximately five-fold. The photo-thermal and photo-mechanical behaviours help CNCs find potential applications on nano-scale photo-controlled thermal generators, mechanical resonators and other opto/electro-mechanical switches.

2 | EXPERIMENTAL DETAILS

CNCs were synthesized by a chemical vapor deposition (CVD) method [19, 20]. The prepared CNCs have unique helical morphology with an average coil diameter of 830 nm and an average pitch of 420 nm. A single CNC was fixed to a tungsten microtip with silver paste and extracted from the prepared CNCs cluster. Figure 1 shows the optical image and the SEM image of a single CNC. It is found that an individual CNC has extremely large aspect ratio to be considered as a natural cantilever.

An optical circuit was set up for observing, stimulating and measuring the photo-mechanical response behaviour of CNC (the experimental schematic is shown in [15]). A focused laser is used to apply photo-mechanical interaction on CNC, the diameter of the laser spot is approximately 4 μm. Through an
RESULTS AND DISCUSSION

3 | RESULTS AND DISCUSSION

3.1 | The static photo-mechanical response characteristics of CNCs

Previous research has demonstrated that a CNC cantilever, no matter exposed to air or water, shows lateral deformation under the irradiation of a focused laser beam, namely a CNC shows mechanical response to laser radiation pressure [13, 15, 21]. The mechanism behind is attributed to the momentum exchange between photons and the CNC.

As shown in Figure 2(a), when a laser beam is focused between two adjacent CNCs, which are exposed to air, the distance between two CNCs becomes larger. Intuitively, the position variations of the two CNCs exactly come from the laser radiation pressure. However, compared with optical irradiation on a single CNC, an “enhancement of photo-mechanical response (EPR)” effect is found. The displacements of the free end of CNC1 and CNC2 (marked as $\Delta s_{1}$ and $\Delta s_{2}$, respectively) are larger than the displacements when they are irradiated separately (marked as $\Delta s_{1}$ and $\Delta s_{2}$, respectively) at the same position without another CNC. It is found that the EPR effect is closely related to the distance between the two CNCs ($D$), the cross length ($L$) and the laser power ($P$). As shown in Figure 2(b–d), the displacements of CNC1 and CNC2 both have positive relationship with $L$ and $P$, while negative relationship with $D$, respectively. During the experimental process, keep CNC2 and laser point still while changing the value of $D$ and $L$ by moving CNC1.

The enhancement factor ($N_i$), which is used to describe the interaction between two CNCs, is written as below:

$$N_i = \frac{\Delta s_{1}/\Delta s_{1}(i = 1, 2)}{\Delta s_{2}}$$

where $\Delta s_{1}$ ($i = 1, 2$) are the displacements of CNCs when they are irradiated together, $\Delta s_{1}$ is the displacement of CNC when it is irradiated solely. For both two CNCs, $N_i \geq 1$. With the distance between two CNCs ($D$) increasing, the laser radiation pressure of CNC1 decreases rapidly, $\Delta s_{1}$ tends to be 0. However, even CNC1 is far away from CNC2 ($D > 10 \mu m$ or $L < -10 \mu m$), $\Delta s_{1}$ is still available. Thus, $N_i$ goes from about 2 to $\infty$ (which is not shown in Figure 2). For CNC2, $N_2$ is also strongly affected by the close relationship between two CNCs. With $D$ increasing or $L$ decreasing, $N_2$ tends to be 1, as shown in Figure 2(b–c), namely, the EPR effect disappears. Conversely, with CNC1 closing to CNC2, the EPR effect becomes more notable. The detailed process is shown in Movies S1 and S2, Supporting Information.

The cause of EPR effect is considered as a result of photo-induced electrical repulsion at first. However, the EPR effect still exists even if the CNCs are electrically grounded or neutralized. Another reasonable hypothesis is the photo-mechanical coupling between CNCs, photons and air. As a kind of black carbon nanomaterial, CNCs have been demonstrated to have excellent photothermal performance. Our previous work has found that the photothermal efficiency of CNCs is approximately 60%, and laser-irradiated CNC absorbs photo energy while releasing thermal energy, which could induce high-speed water flow [22]. In this case, the air around the CNC is heated, especially the air between the two CNCs expands rapidly, which results in an extra repulsive force on the two CNCs. Thus, the practical opto-force of CNC, $F_{\text{opto}}$, can be described as below:

$$F_{\text{opto},i} = F_{\text{photon},i} + F_{\text{air},i}(i = 1, 2),$$

where $F_{\text{photon}}$ and $F_{\text{air}}$ are photon impact force and air propulsion force, respectively. For an individual CNC irradiated alone, $F_{\text{photon}}$ is dominant relative to $F_{\text{air}}$, although the CNC is exposed to laser asymmetrically. For two CNCs irradiated simultaneously, $F_{\text{air}}$ cannot be ignored. Approximately, the enhancement factor is written as below:

$$N_i = \frac{F_{\text{opto}}}{F_{\text{photon},i}} + \frac{F_{\text{air},i}}{F_{\text{photon},i}}(i = 1, 2),$$

where $F_{\text{photon1}}$ and $F_{\text{air1}}$ both depend on the distance between the two CNCs ($D$) and the laser power ($P$). When the two CNCs are far away from each other, CNC2 is irradiated directly while CNC1 is dark. With $D$ increasing or $L$ decreasing, $F_{\text{photon1}}$ tends to be 0, while $F_{\text{air1}}$ is still available due to the photothermal conversion of CNC2; thus $N_1$ goes to infinity first and then decreases to 0 (see details in Movies S1 and S2, Supporting Information). For CNC2, $F_{\text{photon2}}$ keeps constant while $F_{\text{air2}}$ decreases with CNC1 moving farther away; thus, $N_2$ decreases from nearly 2 to 1, namely the EPR effect is gradually weakening.
Although the photo-mechanical coupling between two CNCs are strongly modulated by the laser power, the enhancement factor ($N^2$) is not much influenced, as shown in Figure 2(d), which indicates that $F_{\text{photon}}$ and $F_{\text{air}}$ vary almost equally under laser modulation. Moreover, according to Equations (2) and (3), $F_{\text{air}}$ is approximately equal to $F_{\text{photon}}$, which means the surroundings have great influence on the photo-mechanical interaction between CNCs and laser.

Based on the EPR effect, CNCs are fabricated as an optically actuated tweezer for manipulation of tiny objects, such as cell trapping. As shown in Figure 3, a yeast cell is trapped by optical tweezer firstly, and then moved closing to CNC-based tweezers. The CNC-tweezer is actuated by laser in an opening state for cell. Combined with optical tweezer technology, using CNC-based nano-tweezers for cellular physiological characteristics is a further subject.

### 3.2 The dynamic photo-induced vibration characteristics of CNCs

Our previous work has realized the photo-induced vibration of CNC cantilever using a wave-chopped laser irradiating on the free end, and the amplitude is found to show a positive relationship with laser power [15]. However, the vibration characteristics with the irradiation point of laser have not been investigated. As shown in Figure 4(a–c), for a given CNC with a length of 47 μm, under a laser power of 78 mW, the fixed-end-actuated amplitude is much higher than the free-end-actuated amplitude.

Figure 5(a) shows the amplitude–frequency and amplitude-to-length curves of CNC with different irradiation points. It is found that the maximum fixed-end-actuated amplitude reaches 11.4 μm, which is approximately five-fold higher than free-end-actuated amplitude (2.4 μm). Figure 5(b) indicates that the amplitude-to-length ratio of CNC cantilever reaches as high as 0.24 under fixed-end actuation, which is also five times higher than free-end actuation. Obviously, longer CNC shows larger vibration amplitude. However, longer CNC suffers from greater air damping (generally, the damping factor becomes more than 1 when the length of CNC reaches 90 μm [5, 15]), which would reduce the amplitude. Accordingly, the vibration characteristics of CNC cantilever is dominated by the balance between the length and damping force.

In addition, it is found that for laser irradiation point induced modulation of amplitude generates on curving CNCs, while no such phenomenon occurs on an exactly straight CNC. Our experiments have found the amplitude of straight CNC under chopped laser irradiation decreases monotonously to 0 with the irradiation point moving to the fixed end. A possible hypothesis is that the flex point of curving CNC acts as a non-fixed lever fulcrum; the flex point reduces the effective length of CNC cantilever. Previous work has demonstrated that the resonance frequency is proportional to the squared length of CNC, and CNC show larger amplitude under low-frequency actuation [5, 6]. Thus, free-end-actuated CNC cantilever shows a lower effective resonance frequency and a higher-amplitude vibration. A theoretical analysis and finite analysis simulation for describing the vibration characteristics of curving CNCs is a further project.

### 4 CONCLUSION

The photo-mechanical response characteristics of an individual CNC cantilever is investigated. Due to the excellent photothermal ability of CNCs, an “EPR” effect is found when two adjacent CNCs are irradiated by a laser, which results from the photothermal coupling between CNCs and surroundings. Moreover, a chopped-laser-induced vibration of curving CNC with tunable amplitude is realized. The fixed-end-actuated amplitude-to-length ratio is approximately five-fold higher than free-end-actuated ratio, which reaches as high as 0.24. Because of the excellent photothermal ability and photomechanical response, CNCs have promising applications in...
the fields of micro/nano photo-activated thermal generators, photo-actuators and photo-controlled bio-tweezers.

**ACKNOWLEDGEMENTS**

This work is supported by the Scientific and Technological Innovation Programs of Higher Education Institutions in Shanxi (No. 2020L0538) and Science Research Project Fund of Xinzhou Teachers University (No. 2019KY06).

P. Wang1
Q. L. Wang1
C. H. Deng2
L. J. Pan3

1 Department of Physics, Xinzhou Teachers University, Xinzhou, Shanxi, P. R. China
2 Center on Nanoenergy Research, School of Physical Science and Technology, Guangxi University, Nanning, Guangxi, P. R. China
3 School of Physics, Dalian University of Technology, Dalian, Liaoning, P. R. China

Correspondence

P. Wang, Department of Physics, Xinzhou Teachers University, Xinzhou 034000, Shanxi, P. R. China.
Email: WP15242630598@yeah.net

**ORCID**

P. Wang https://orcid.org/0000-0001-5738-2247

**REFERENCES**

1. Li, C.W., et al.: CNC-Al2O3-Ti: A new unit for micro scale strain sensing. RSC Adv. 6(109), 107683–107688 (2016).
2. Wang, P., et al.: Tearing-off method based on single carbon nanocoil for liquid surface tension measurement. Jpn. J. Appl. Phys. 55(11), 118001 (2016).
3. Wang, P., et al.: A carbon nanocoil-based flexible tip for a live cell study of mechanotransduction and electro-physiological characteristics. J. Mater. Chem. B 8, 1405–1410 (2020).
4. Volodin, A., et al.: Coiled carbon nanotubes as self-sensing mechanical resonators. Nano Lett. 9(9), 1775–1779 (2004).
5. Deng, C.H., et al.: Electromechanical vibration of carbon nanocoils. Carbon 81, 758–766 (2015).
6. Saini, D., et al.: Mechanical resonances of helically coiled carbon nanowires. Sci. Rep. 4, 1–6 (2014)
7. Volodin, A., et al.: AFM detection of the mechanical resonances of coiled carbon nanotubes. Appl. Phys. A. Mater. 72, S75–S78 (2001).
8. Xiong, W., et al.: Laser-directed assembly of aligned carbon nanotubes in three dimensions for multifunctional device fabrication. Adv. Mater. 28(10), 2002–2009 (2016).
9. Sato, M., et al.: Optical manipulation of intrinsic localized vibrational energy in cantilever arrays. Europhys. Lett. 66(3), 318–323 (2004).
10. Zhang, J., et al.: Multidimensional manipulation of carbon nanotube bundles with optical tweezers. Appl. Phys. Lett. 88(5), 1–3 (2006).
11. Yan, Z.J., et al.: Three-dimensional optical trapping and manipulation of single silver nanowires. Nano Lett. 12(10), 5155–5161 (2012).
12. Spesyvtseva, S.E.S., Shoji, S., Kawata, S.: Chirality-selective optical scattering force on single-walled carbon nanotubes. Phys. Rev. Appl. 3(4), 044003 (2015).
13. Lv, J.T., et al.: Carbon nanocoils manipulated by optical tweezers. In: 5th International Symposium on Advanced Optical Manufacturing and Testing Technologies: Smart Structures and Materials in Manufacturing and Testing, vol. 7659, p. 765905. SPIE, Bellingham, WA (2010).
14. Wang, S.B., Chan, C.T.: Lateral optical force on chiral particles near a surface. Nat. Commun. 5, 1–8 (2014).
15. Wang, P., et al.: Optically actuated carbon nanocoils. Nano 13(10), 1850112 (2018).
16. Wu, J., et al.: Carbon nanocoil-based fast-response and flexible humidity sensor for multifunctional applications. ACS Appl. Mater. Interfaces 11(4), 4242–4251 (2019).
17. Ma, H., et al.: Photo-driven nanoactuators based on carbon nanocoils and vanadium dioxide bimorphs. Nanoscale 10(23), 11158–11164 (2018).
18. Ma, H., et al.: Infrared micro-detectors with high sensitivity and high response speed using VO2-coated helical carbon nanocoils. J. Mater. Chem. C 7(39), 12095–12103 (2019).
19. Gai, X., et al.: Highly efficient synthesis of carbon nanocoils on alumina spheres. RSC Adv. 6(36), 30125–30129 (2016).
20. Zhao, Y., et al.: Growth of carbon nanocoils by porous α-Fe2O3/SnO2 catalyst and its buckypaper for high efficient adsorption. Nano-Micro Lett. 12, 23 (2020).
21. Liu, Y.L., Shen, J., Sun, Y.M, (eds.): The mechanical oscillation of a single carbon nanocoil driven by a focused laser beam. In: IOP Conference Series: Materials Science and Engineering. IOP Publishing Ltd, Bristol, England (2019).
22. Wang, P., et al.: Highly efficient near-infrared photothermal conversion of a single carbon nanocoil indicated by cell ejection. J. Phys. Chem. C 122(48), 27696–27701 (2018).

**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.