Light-actuation of carbon nanotubes in liquids

Yujie Liu[1], Chunhui Zhu[1], Emmanuel Flahaut[2,3], Fengqiu Wang[1]*

[1]School of Electronic Science and Engineering, Nanjing University, Nanjing 210093, China
[2]CNRS; Institut Carnot Cirimat; F-31062 Toulouse, France.
[3]Universite de Toulouse; UPS, INP, Institut Carnot Cirimat; 118, route de Narbonne, F-31062 Toulouse cedex 9, France.

E-mail address: fwang@nju.edu.cn

Abstract: We observed a novel phenomenon where single-wall carbon nanotube flocculations can be photo-actuated in liquids by either sunlight or laser irradiation. The light-actuation phenomenon is found highly repeatable.

OCIS codes: (160.5335) Photosensitive materials; (160.4236) Nanomaterials

1. Introduction

Light has been an ideal and ubiquitous energy source for a variety of physical systems. Over the past decade, as driven by the emerging field of photomechanical research, it becomes increasingly desirable to develop materials or structures that can directly convert light stimulus into mechanical work. For example, a bulk graphene sponge has been observed to be propelled effectively by light illumination in vacuum [1]. Single-wall carbon nanotube (SWNT), a hollow cylinder that is formed by a rolled-up graphene, features strong light-matter interactions and shows promise for photoactuation applications [2, 3]. Photo-induced charge build-up at the interfaces has been identified as the main underlying mechanism [4]. However, the photothermal effect of SWNTs in an aqueous environment has not been investigated thus far. In particular, SWNTs with photo-actuation capabilities in aqueous environment are envisioned to bring about novel biomedical applications in drug delivery, cancer diagnosis and phototherapy [5].

Here, we uncovered for the first time an intriguing photothermal property of SWNTs that when dispersed in liquids in the form of flocculations, SWNTs are capable of converting light energy directly into mechanical movements. We further confirm that the phenomenon can be triggered by both sunlight and laser sources. Such a novel photo-actuation capability of SWNTs opens up the possibility for many practical applications, including underwater decontamination, optical valve in aqueous environments and safe handling of dangerous liquid samples.

2. Experimental

As shown in Fig.1, SWNTs soot (purity: > 90%, Carbon solutions Inc.) were added to alcohol in a glass vial at a concentration of 0.01 wt.%. Then the mixture was tip-sonicated for ~30 minutes. With such a treatment, the resulting SWNTs were found evenly suspended in alcohol. After settling for 12 hours, the SWNTs aggregated to SWNT flocculations. For the light-actuation experiments, the phials filled with SWNT flocculations were illuminated under ambient condition.

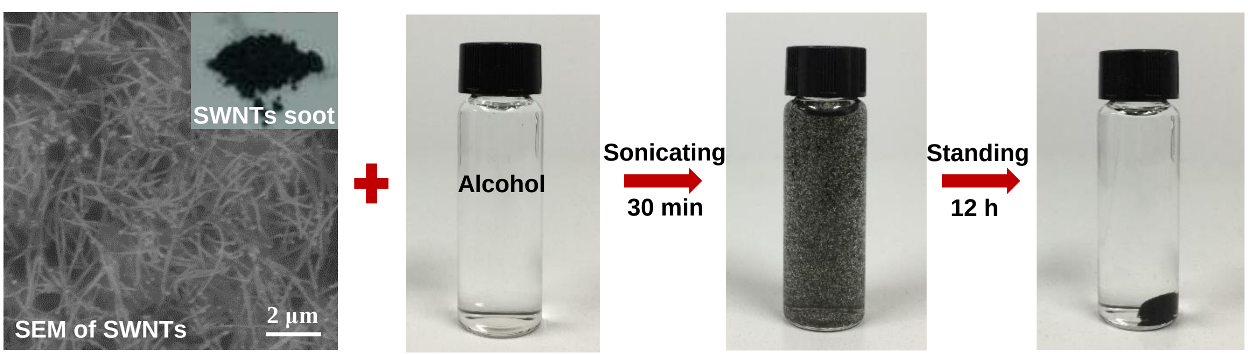

Figure 1. Fabrication process for SWNT flocculations in alcohol.

The intriguing response of the SWNT flocculations in alcohol under sunlight was shown in Fig. 2(a). At the beginning, we placed the phial in a shadowed place, the SWNT flocculations remained stationary at the bottom of the phial. When exposed to sunlight irradiation, the SWNT flocculations were observed to float upwards within a few seconds until it reached the surface of the solution. Interestingly, once moved back to a shadowed place, the SWNT flocculations began to fall back towards the bottom of the container. The photo-actuation response to sunlight was found highly reproducible. We further used multiple lasers including the wavelength of 405, 532, 650, 1550 and 2000 nm. Fig. 2(b) shows the visible light actuation process under 532 nm irradiation. The SWNTs can be lifted up although the motion is slightly slower compared with the case of sunlight irradiation. This is somehow expected as the SWNT bundles used can absorb efficiently across UV to the near-IR range [6]. In addition, it is worth noting that different power densities can influence the photoresponse, *e.g.*, when we increased the output power of the laser, the SWNT flocculations were lifted faster than the lower power.

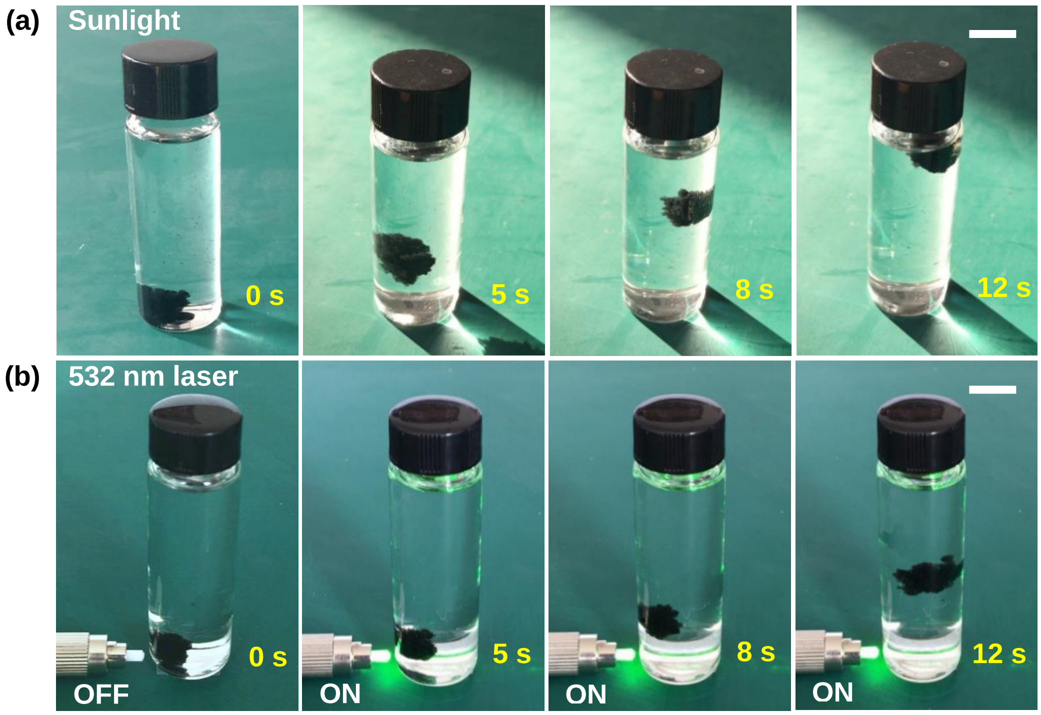

Figure 2. Optical images of the actuation process of the SWNTs in alcohol at different time. (a) Under sunlight. The intensity of the stimulated sunlight is estimated ~40 mW cm^{-2} by a thermal power meter (Scale bar: 1 cm). (b) Under 532 nm laser illumination. The laser is incident from the left, with the intensity of ~80 mW cm^{-2} (Scale bar: 1 cm).

As a further demonstration of the light-actuation, other liquids (including water and N-methyl-2-pyrrolidone) had been used to disperse SWNTs by the procedure described above. SWNT flocculations in these liquids showed similar photo-actuation behavior. The speeds of the upward movement are slightly different, which was probably attributed to the different density and kinematic viscosity coefficients of different liquids. To verify light absorption of SWNTs plays the key role in the observed effect, we placed the container in an oven at 80°C. No floating of SWNTs was observed. We attribute local heating induced by SWNTs light absorption to be the main underlying mechanism. This is supported by the fact that only upright movement is observed regardless of the actual direction of incident excitation light. Other effects, such as laser induced diameter expansion in SWNTs, might also play a role [7, 8].

3. Conclusion

We observed an interesting phenomenon where SWNT flocculations can be effectively photo-actuated in the liquid. Such a photothermal effect is power and wavelength-dependent and can potentially lead to wide-ranging applications in environmental and medical research.

References

[1] T. Zhang, et al., "Macroscopic and direct light propulsion of bulk graphene material," Nat. Photon. **9**, 471-477 (2015).
[2] H. Koerner, et al., "Remotely actuated polymer nanocomposites—stress-recovery of carbon-nanotube-filled thermoplastic elastomers," Nat. Mater. **3**, 115-120 (2004).
[3] S. V. Ahir and E. M. Terentjev, "Photomechanical actuation in polymer-nanotube composites," Nat. Mater. **4**, 491-495 (2005)
[4] X. Zhang et al., "Photoactuators and motors based on carbon nanotubes with selective chirality distributions," Nat. Commun. **5**, 2983 (2014).
[5] Z. Liu, et al., "Carbon nanotubes in biology and medicine: in vitro and in vivo detection, imaging and drug delivery," Nano Res. **2**, 85-120 (2009).
[6] W. Li, et al. "716 nm deep-red passively Q-switched Pr:ZBLAN all-fiber laser using a carbon-nanotube saturable absorber," Optics letters **42**, 671-674 (2017).
[7] C. Sciascia. "Long lived photo excitations in (6, 5) carbon nanotubes," Eur. Phys. J. B **75**, 115-120 (2010).
[8] G. Cao, et al., "Clocking the anisotropic lattice dynamics of multi-walled carbon nanotubes by four-dimensional ultrafast transmission electron microscopy," Scientific Reports **5**, 8404 (2015).