Journal of Physics: Conference Series **194** (2009) 012054 doi:10.1088/1742-6596/194/1/012054

Broadband light emission from optically-trapped carbon nanotubes

Hema Ramachandran[1], A K Dharmadhikari[2], J A Dharmadhikari[3], D Mathur[2,3]

[1] Raman Research Institute, Sadashiv Nagar, Bangalore 560 080, India.

[2] Tata Institute of Fundamental Research, 1, Homi Bhabha Road , Mumbai 400 005, India.

[3] UM-DAE Centre for Excellence in Basic Sciences, University of Mumbai, Kalina Campus, Santa Cruz East, Mumbai 400 098, India.

hema@rri.res.in

Abstract: Optical micromanipulation of carbon nanotubes (CNT), that has hitherto been elusive, has been achieved in an aqueous suspension of CNTs in an optical tweezers setup, via the mediation of microbubbles. These microbubbles are formed when CNT bundles are brought to the focal volume. With the bubbles themselves being easily trappable in the tweezers, the CNTs adhered to the surface of the microbubbles can now be held immobilised. CNTs held in the optical trap focus are found to emit bright light in the visible, which may be a sustained glow, or an uncontrolled flare. These observations and the underlying mechanisms will be discussed in the talk.

Conventionally, white light generation refers to broadband light resulting from high order nonlinear processes that occur in materials that are subjected to high incident light intensities. In this Progress Report we discuss white light generation from nanosources under milliwatt cw illumination, namely CNTs in optical tweezers.

Carbon nanotubes are a "wonder material" with very many interesting properties. The very high aspect ratio of their dimensions, and their structural stability, give rise to unique properties. High tensile strength, high electrical conductivity, good semiconducting properties of some nanotubes have given CNTs a versatility unmatched by other known materials. Our experiments were aimed at trapping and manipulating CNTs optically, in a tweezers setup operating at 1064nm[1]. Experiments were conducted on carbon nanotubes that were 1.2 to 1.5 nm in diameter and a few microns in length. The CNTs were agglomerated in the form of bundles, of sizes varying from 1 to 10 μm. In order to select as small bundles as possible, the nanotubes were suspended in water with 1% sodium dodecyl sulphate as surfactant, centrifuged, and the supernatant used. Attempts to optically trap the CNTs showed that they were vigorously repelled from the tweezers focus [2]. However, when brought close

to the focal volume fast enough that the tweezers could not kick it away, microbubbles were seen to form in the fluid, invariably emerging from the ends of CNT bundles (Fig. 1).

The size and number of bubbles could be simply and reproducibly controlled by adjusting the tweezer light intensity or its focussing. Bubbles as large as 100 μm (diameter) could be readily created; we were restricted by our field of view. Most interestingly, neighbouring CNT bundles were found to be attracted to the microbubbles; they moved rapidly through the fluid and adhered onto the microbubble's surface (Fig. 2). As the microbubbles could easily be trapped in the tweezer, the CNTs that were originally repelled by the tweezer light could now be spatially immobilized and optically manipulated.

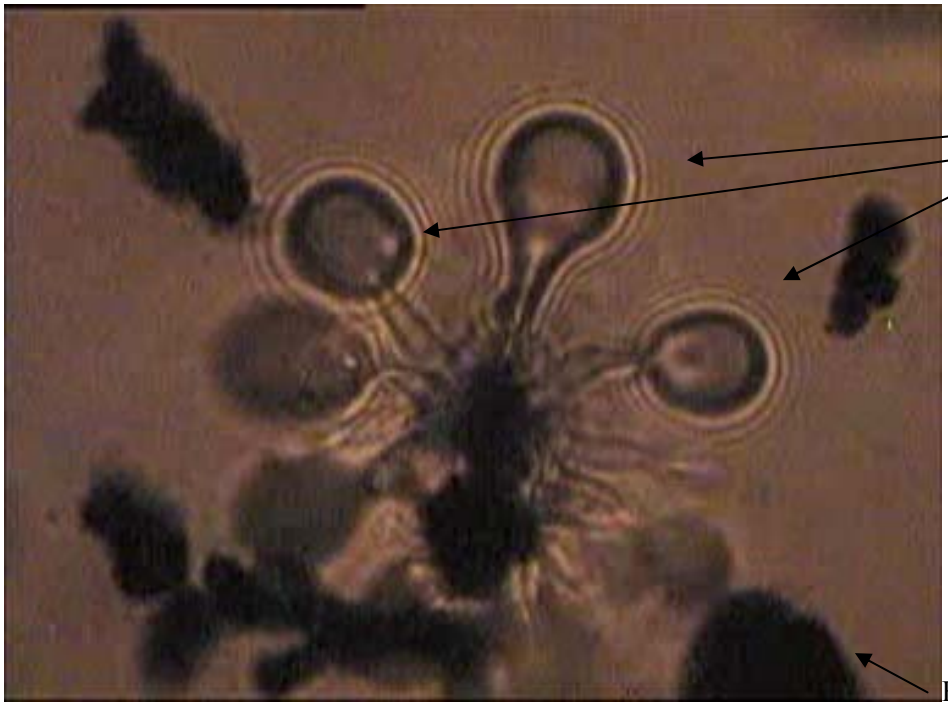

Figure 1: Microbubbles originating from a CNT bundle at the tweezer focal volume (centre of the picture).

The observations mentioned so far can be interpreted thus – tweezers work on the principle of dipole force. In a light field with an electric field gradient (as in tightly focused light), an object experiences a force given by:

$$F = \alpha \left| \text{grad}(E)^2 \right| /2$$

where grad is the gradient in the electric field. The polarizability, α, away from resonance is positive for light to the red of a resonance and is negative for light to the blue. Thus in a focused beam, an object can be immobilized at an intensity maximum using red-detuned light.

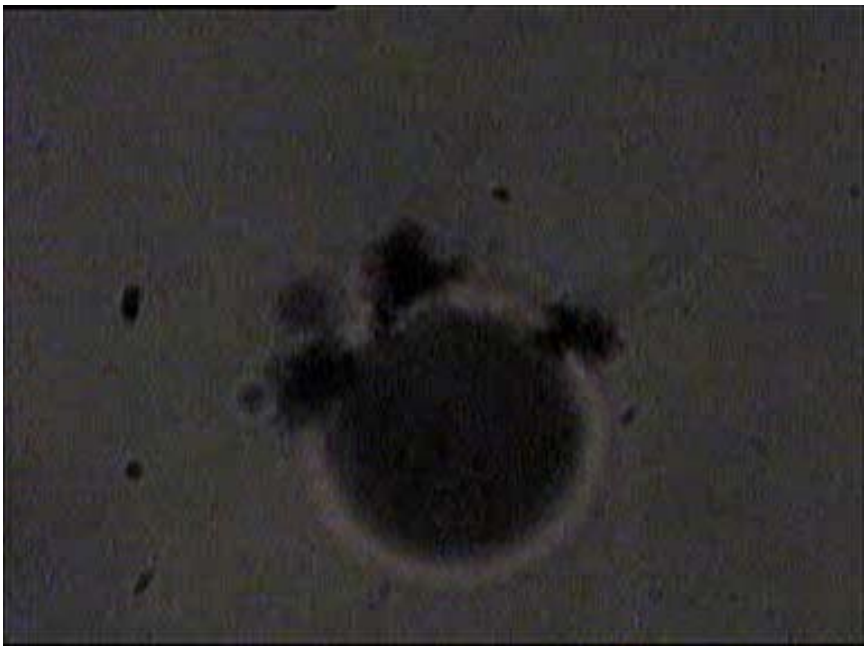

Figure 2: CNT bundles in the vicinity are attracted to the microbubble; they adhere to the surface of the bubble.

The CNTs we used had an absorption profile as shown in Fig. 3. The tweezer light is blue detuned to a prominent absorption feature, and thus the focused light provides a repelling force. However, when brought to the vicinity of the focal volume at high translation speeds of the tweezer sample stage, the repelling force of the tweezer light could be overcome and the CNTs could remain within the trap volume for some time, during which they very efficiently absorb the tweezer light and get heated. The localised heating causes the expansion and vaporization of fluid both within individual tubes and between the tubes of a bundle; it is the expulsion of this hot matter that creates the microbubbles. While the manipulation of the size and number of bubbles by means of light intensity is easily understood in terms of this picture, the cause for the attraction of the CNTs to the bubbles is not clear. Surface tension and surface charge accumulation are possibilities that are worth exploring.

Microbubble-mediated optical trapping of CNTs is found to hold these nano-objects immobilized at the laser focus indefinitely. The most spectacular observation on CNTs in the optical tweezers has been the emission of very bright emission of light in the visible region of the spectrum. The emission, visible to the naked eye was obtained even at tweezer powers as low as a few milliwatt. The emission appears as a continuous glow, orange-red in colour, which changes to yellowish colour and then to bluish violet on increasing the laser irradiance. It may be noted that the tweezer light is in the infrared (1064 nm), and has very low cw power (less than 5 mW). On increasing the irradiance further, either by higher input power or tighter focusing of the tweezer light, uncontrolled flares were seen, often with the bundles breaking up violently and the debris being expelled away very rapidly.

Spectral analysis of the continuous glow showed that the emission spread over the entire range of the spectrometer 400-1000 nm, peaking in the visible (600 nm-700 nm). An increase in the intensity of the tweezer light caused the overall emission to increase in strength and the peak to shift to shorter wavelengths, indicative of a blackbody emission mechanism. A functional fit to the blackbody function, however, showed deviations at either ends of the spectra. This could possibly arise from the response of our spectrometer or self-absorption by the sample, or the presence of some non-linear

effect. Further work is in progress. Nevertheless, the systematic shift in emission wavelength as well as emission intensity undoubtedly indicates a predominantly blackbody emission mechanism. We point out that a peak wavelength of ~570 nm in a blackbody emitter would correspond to a local temperature exceeding 5000K – a nano-sun ! At very high irradiance, the CNTs ignite as evidenced by the flares and the catastrophic rupture – a "nano-explosion".

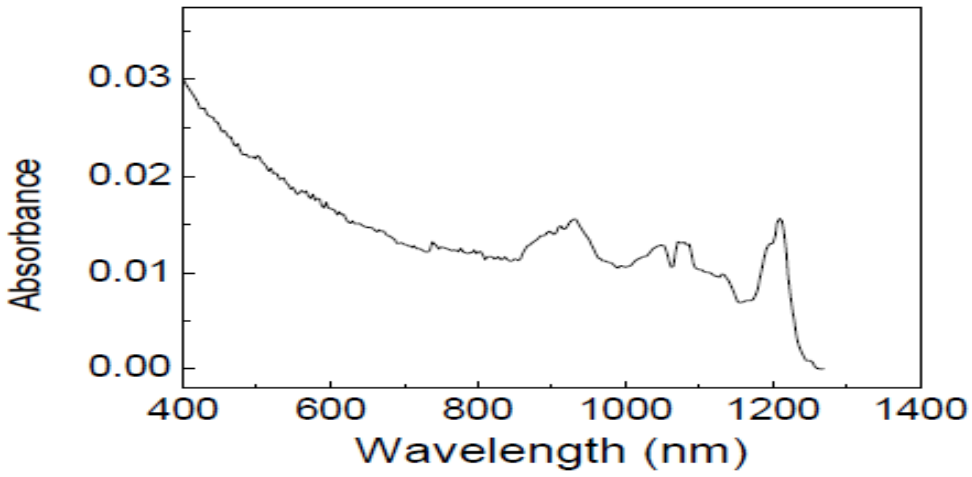

Figure 3: Absorption profile of the CNTs used by us.

.

Figure 4: Sustained emission from a CNT bundle.

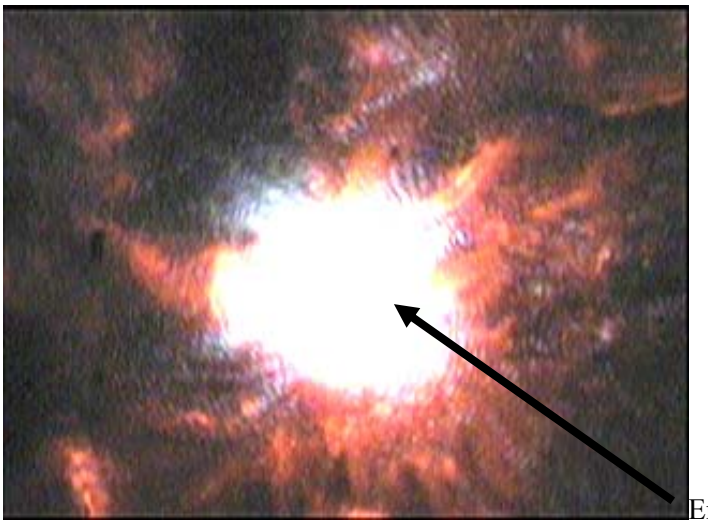

Figure 5: A catastrophic event, resulting in violent break-up of a CNT bundle.

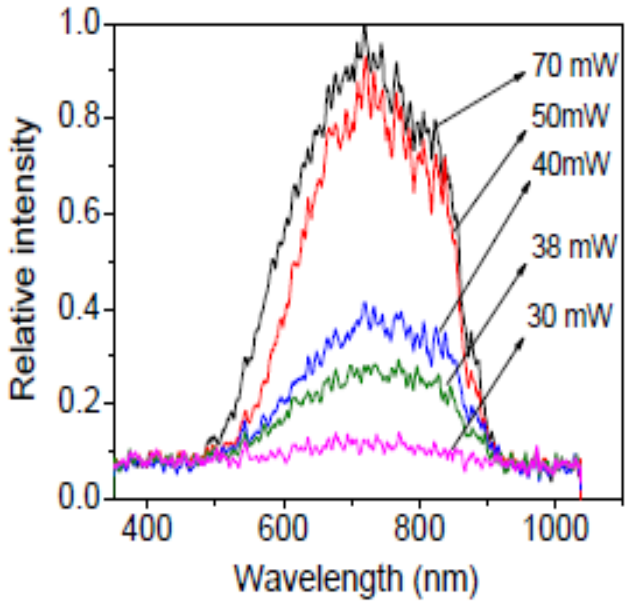

Figure 6: Spectra of light emitted from CNT bundles exposed to various input light powers.

It must be mentioned that light emission has indeed been observed from CNTs earlier, but under completely different conditions. Joule heating of current carrying nano-filaments or nano-ropes [3-5] during field emission when isolated nanotubes are subject to high voltages [6,7], and irradiation of CNTs by high intensity nanosecond pulsed lasers [8] have been some situations reported to have caused light emission from CNTs. In all these cases, however, the emission has been at wavelengths longer than the visible. Further, earlier attempts to associate the emission to blackbody temperatures have estimated a maximum of 2000 K [8]. We believe that our work is qualitatively different in that

extremely low power irradiation is used to not only optically trap CNT bundles, via the mediation of light-generated microbubbles, but the same low power irradiation also gives rise to emission of broadband light from a spatially miniscule nanosource [9].

Spatially-controllable nano-sources of broadband emission are of intrinsic interest to the atomic, molecular and optical sciences community. Over and above such interest, our observations open up a large number of possibilities for applications. The creation of microbubbles in controllable fashion could find application in printing technology, control of chemical reactions, micro-mixing of fluids, to mention a few. The optical trapping of CNTs promises applications in biomedicine. The continuous glow could be used as controllable light source for biomedical engineering applications, and the ignition could be used for photodynamic therapy in medicine. Truly, our imagination is the limit to applications of this versatile material – the carbon nanotube !

Acknowledgements: The assistance of Gopika Ramanandan and Kapil Bambadekar with parts of the experimental work is gratefully acknowledged. GR's work was supported by the Indian Academy of Sciences in the form of a Summer Fellowship.

References

1. Dharmadhikari J A and Mathur D , "Using an optical trap to fold and align single red blood cells," Curr. Sci. 2004, **86**, 1432–1437 .

2. The use tweezers operating at 1064 nm has invariably led to repulsion of CNTs from the focal region; holographic tweezers at shorter wavelength (532 nm, as by Plewa J, Tanner E, Mueth D M, and Grier D G, Opt. Exp. 2004, **12**, 1978) have been shown to trap CNTs.

3. Li P, Jiang K, Liu M, Li Q, and Fan S, "Polarized incandescent light emission from carbon nanotubes," Appl. Phys. Lett. 2003, **82**, 1763-1765

4. Wei J, Zhu H, and Wu D, "Carbon nanotube filaments in household light bulbs," Appl. Phys. Lett. 2004 **84**, 4869-4871.

5. Li C, Wang K, Wei J, Wei B, Zhu H, Wang Z, Luo J, Liu W, Zheng M, and Wu D, "Luminescence of carbon nanotube bulbs," Chinese Science Bulletin 2007, **52,** 113-117.

6. Bonard J M, Stöckli T, Maier F, de Heer W A, and Châtelain A, "Field-Emission-Induced Luminescence from carbon nanotubes," Phys. Rev. Lett. 1998, **81**, 1441-1444.

7. Sveningsson M, Jönsson M, Nerushev O A, Rohmund F, and Campbell E E B, "Blackbody radiation from resistively heated multiwalled carbon nanotubes during field emission", 2002 Appl. Phys. Lett. **81**, 1095- 1097

8. Zeng H, Yang C, Dai J, and Cui X, "Light-induced incandescence of SWNT," J. Phys. Chem. C. 2008, **112**, 4172-4175.

9. Ramanandan G, Dharmadhikari A K, Dharmadhikari J A, Ramachandran H, and Mathur D, "Bright visible emission from carbon nanotubes spatially constrained on a micro-bubble," Opt. Exp. 2009, **17,** 9614.