Electromagnetic excitation of nano-carbon in vacuum

Shaomin Wang, Laigui Hu, Binzhi Zhang, and Daomu Zhao

Department of Physics, Zhejiang University, Hangzhou 310027, China
optics@zju.edu.cn

Zhiyi Wei and Zhiguo Zhang

Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China

Abstract: Nano-carbon as lighting source is demonstrated in this paper. The characterized nano-radiation from nano-carbon, excited by different lasers in vacuum, is observed when laser intensity is over a threshold. With lower excitation threshold and smaller white light source, nano-carbon is more applicable to be as lighting system than the others in scientific experiments. White light emission of nano-carbon induced by more practicable electromagnetic excitation (microwave) is also demonstrated, which is caused by the faradic heating of the metal substrates, with molecular spectra and better color rendering. Lighting systems comprised of nano-carbon may become one of the considerable directions in optics.

OCIS codes: (350.5340) Photothermal effects; (140.5960) Semiconductor lasers; (350.4010) Microwaves

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1. Introduction

Nanomaterials have received an increasing interest for their novel properties, especially for their optical properties [1-4]. Thus many implements such as light-emitting diodes (LEDs) and laser diodes (LDs) based on their quantum optical effects are fabricated [5,6], while few based on the classic effects (e.g., the thermal radiation from nanomaterials) are obtained. Recently, high efficient laser-induced white and bright emission from nano-carbon in Crookes radiometer (also named light mill) is observed accidentally when the laser intensity is over a threshold (1 kW/cm^2 – 1 MW/cm^2) [7,8]. Its transforming efficiency is found to be more than 80%, which is quite different from the normal photoluminescence. In this paper, we show that it is the thermal radiation from nano-carbon (nano-radiation) which often makes us confuse it with photoluminescence (PL) [9,10]. With good color rendering, this white radiation from nano-carbon may be an ideal lighting source, even as a white point source in the scientific experiments.

Over the last decade, many applications of nano-carbon have been explored as filler in composite materials, electrodes for fuel cells, individual functional elements of a device and so on [11]. Its application in lighting was also attempted by A. N. Obraztsov *et al*. who developed a vacuum cathodoluminescence lighting device [12]. In our work, nano-radiation from nano-carbon is studied and new applications of nano-carbon in optics are found, i.e., as a white point source and lamps excited by lasers and microwave. Applying the more practicable electromagnetic excitation (microwave), we find a new white lighting system with metal substrates. Some experiments show the motion of charge such as current and arcing effect [13] catalyzes this process, which may vaporize the nano-carbon and thus permanent C_2 white emission is also obtained which is more suitable to be as the lighting system.

2. Laser excitation of nano-carbon

A Crookes radiometer made in Germany 50 years ago, which is famous for demonstrations of kinetic theory of gases or light pressure (only under the higher vacuum condition), is used here and a focused strained multiple quantum-well laser diode (MQW-LD) beam with 655-nm wavelength and 35-mW power (M-65-003-20, fabricated by E-O Communication Inc. US) is employed to strike the vanes of the radiometer. Normally, what drives the vanes (aluminium foils, which are blackened on one side by the nano-carbon) to spin is not light pressure but the photothermic effects that cause the residual air near the blackened side of vanes warmer than that near the silvered side. In our case, the stronger the laser intensity, the more energy which heats up the blackened side of the vanes, and it causes the vanes to spin faster and faster as the laser intensity gets higher. However, when the laser intensity is over a threshold, we find the vanes stop spinning and even rotating inversely which disobeys the normal phenomenon [14], just like it does in cold water [15]. Simultaneously, white light emission is observed from the nano-carbon as shown in Fig. 1(a) and 1(b), a vane of the radiometer is located at around the focus of the laser beam (655 nm), the laser energy is absorbed and transformed into dazzling white light emission. Its transforming efficiency is estimated to be >80% by series instruments including the integrating sphere and a NOVA laser power monitor with a PD300-UV head (OPHIR Optronics Ltd., US). Spectra from nano-carbon are almost independence of

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excitation wavelength, see Fig. 1(c) collected by the WDP500-D plane grating scanning monochromator (over the wavelength range of 200-900 nm) with a scaled photomultiplier (R955 Hamamatsu Photonics K. K., Japan). The variation of the excited intensity versus wavelength is due to the different excitation laser intensity. No feature peaks and no structural changes are observed in these processes. Figure 1(a) is the magnification of the pane in Fig. 1(b), in which the upper small yellow spot is excited by the side lobe of the laser beam. Since the laser intensity in the center of beam is mostly stronger than that in the side, light in the side area of laser beam where light intensity is below the threshold can not excite carbon particles to emit white light, which causes the dimension of the white spot smaller than that of the beam width (including red halos). The focused output of laser beams is often regarded as a point light source in scientific experiments. Now the white radiation from the nano-carbon with smaller dimension than beam width of LDs may provide a more ideal point source with 4π emission angle.

Figure 1(d) is the transmission electron microscope (TEM) picture of nano-carbon and its dimension is estimated to be 30-100 nm. Under the same conditions, nano-carbon (such as deposited soot particles, carbon nanotubes, nano-C_{60} and graphite powders) with different substrates is encased in an evacuated chamber, and similar phenomena can also be observed. However, the amorphous nano-carbon is the best. Furthermore, no such emissions are observed from bulk materials.

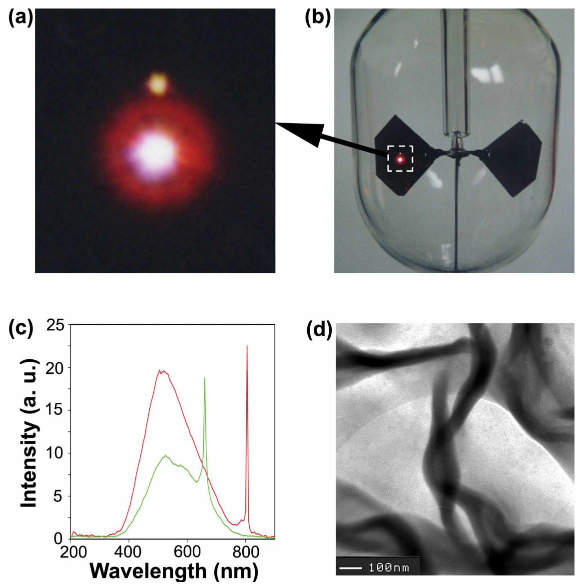

Fig. 1. Demonstration of the laser-induced characterized nano-radiation from nano-carbon covering the vanes of the Crookes radiometer. (a) The magnification of the pane in Fig. 1(b). (b) One vane of the radiometer is illuminated on the blackened side by a focused red (λ = 655 nm) LD beam. (c) Spectra of the white light emission induced by two different LDs with 806-nm wavelength (250-mW power, red line) and 655-nm wavelength (35-mW power, green line). (d) TEM picture of the nano-carbon particles.

Considering this emission as thermal radiation under nano-dimension primarily, we investigate it in theory. Spectral radiant flux of thermal radiation from a particle is expressed as

$$\Phi_{\lambda}(r,T) = 4\pi r^2 Q_{abs}(r,\lambda) P_{\lambda}(T), \qquad (1)$$

where $P_{\lambda}(T)$ is the spectral radiant exitance of a Planckian radiator at temperature T. $Q_{abs}(r, \lambda)$, as a function of the radius r and the wavelength λ, is the absorption efficiency. If the Rayleigh criterion for particles ($2\pi r/\lambda<1$) is satisfied, then [16]

$$Q_{abs}(r,\lambda) = \frac{8\pi r}{\lambda} \mathrm{Im}\left[\frac{m^2-1}{m^2+2}\right]. \tag{2}$$

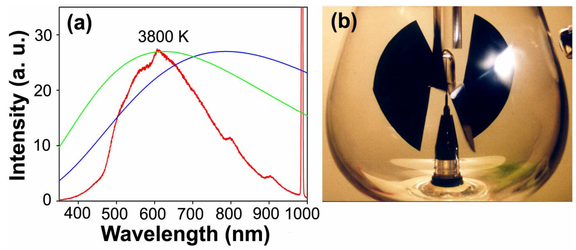

Fig. 2. (a) Spectra of laser-induced radiation from carbon nanoparticles (red line) and theoretical simulation of blackbody radiation (blue line), radiation from a carbon nano-particle (green line) at temperature 3800 K. (b) Similar phenomenon is still observed in the modified radiometer by us.

For nanoparticles, this criterion can be easy to be satisfied. In our condition (e.g. r ~ 25 nm), the spectrum is simulated as shown in Fig. 2(a) (green line). Data of the refractive index m(λ) are derived from Ref. [17] in which refractive indexes of soot particles in the wavelength range $0.4 \le \lambda \le 30$ μ m have been calculated. At about 3800 K (still smaller than its melting point ~3915 K), the theoretic spectrum is closer to our observation (red line). To confirm it as the thermal radiation under nano-dimension, two mode-locked femtosecond (fs) lasers operating at a wavelength of 800 nm with the same pulse duration, different repetition rates and different pulse powers (30 fs, 76 MHz, 10^5 W, average power ~0.8 W; and 30 fs, 10 Hz, 10^{12} W, average power ~ 0.5 W) are adopted. Similar emission can be observed for the former laser with repetition rate of 76 MHz. But no emission is obtained for the latter. Therefore, it acts in accord with thermal radiation under nano-dimension. Obviously, energy absorbed from the laser with repetition rate of 10 Hz is not enough to heat the carbon particles to 3800 K due to the long interval between pulses, although its pulse power is higher than that of the former

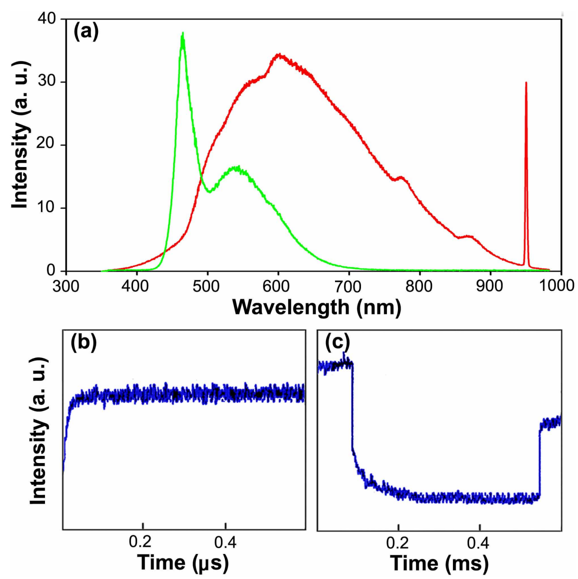

Fig. 3. Features of the characterized nano-radiation. (a) Comparison of spectra between the nano-radiation of nano-carbon (red line) and normal LED (green line). (b) Oscillograph trace of emission delay and (c) emission decay in the time resolved experiments (recorded by a photomultiplier and HAMEG 30 MHz Analog/Digital Scope HM 305).

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laser. Hence thermal radiation under nano-dimension (nano-radiation) plays a main role. Obviously, no white light emission from bulk carbon is due to the higher excitation threshold. Compared with blackbody radiation at 3800 K [blue line in Fig. 2(a)], the nano-radiation of carbon particles has the superiority that it can emit white light at lower temperature. A modified Crookes radiometer [Fig. 2(b)] with three vanes is adopted and the same phenomenon still exists.

As we know, the peak of human eye sensitivity curve is at about 555 nm [18], which is much close to the peak of nano-radiation [see the red line in Fig. 3(a)]. Spectra are collected by a high-resolution spectrometer (Ocean Optics USB2000, US) with a Si charge coupled device (CCD) array detector. A focused quantum-well structured InGaAs/GaAs/AlGaAs LD (fabricated by Hi-Tech Optoelectronics Co., Ltd., China, 980 nm, with its highest intensity $\sim 10^6$ W/cm^2, cw) is used here. From Fig. 3(a), the full width at half maximum (FWHM) of the nano-radiation is estimated to be 250 nm. And the spectrum almost covers the full visible region. That's why the radiation looks white and even dazzles human eyes. These make it possible to be as a nice lighting system with better color rendering. For comparison, spectrum of a normal LED is also collected [see the green line in Fig. 3(a)]. Using the LD (980 nm) with 1 kHz square pulse power supply and photomultiplier tube (R955 Hamamatsu Photonics K. K., Japan), time resolved experiments are studied. Data of radiation intensity are recorded as shown in Fig. 3(b) and 3(c). Since the rising time of the pulse is smaller than 0.1μs [Fig. 3(b)], the emission delay is roughly estimated to be 0.1 μs and its emission decay is about 10^{-1} ms [Fig. 3(c)], respectively, which is much different from common thermal radiation from bulk materials.

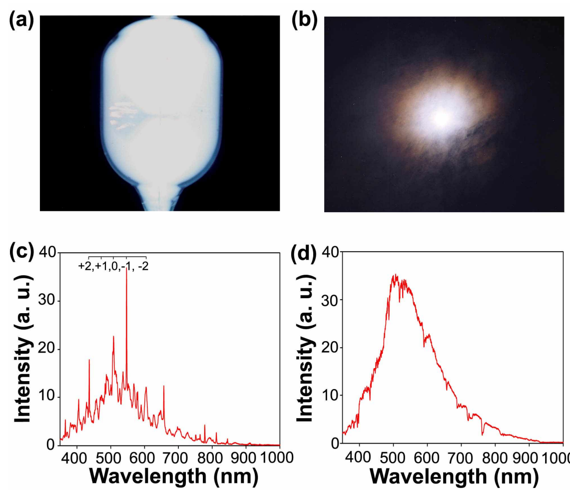

Fig. 4. Demonstration of the microwave-induced white light emission. (a) Photograph of this emission from the radiometer. (b) Photograph of the sun under the same exposure condition for comparison. (c) Spectrum of the microwave-induced emission. (d) Spectrum of the sun light.

3. Microwave excitation of nano-carbon

When we consider the practicability of this optical emission, other electromagnetic excitation (microwave) is tried. A magnetron tube is also employed to stimulate the radiometer. Although nano-radiation from the carbon particles covering the vanes is still observed [see the white spots on the vanes in Fig. 4(a)], the whole chamber can also emit white light (this can be realized even in a microwave oven), which is different from the situation mentioned above. Obviously, overheating leads to vaporization of the nano-carbon. Hence the temperature of carbon particles rises to be more than 3915 K. Spectrum of this emission is collected as shown in Fig. 4(c), which is much close to that of the sun [Fig. 4(b) and 4(d)]. Moreover, the C_2

emission in the Δv = -2, -1, 0, +1, and +2 vibrational sequences of the Swan system ($d^3\Pi_g$-$a^3\Pi_u$) [19, 20] is observed [see Fig. 4(c)]. Carbon particles are mainly evaporated into the form of C_2. Therefore, the C_2 emission and thermal radiation are dominant in this process, which make it more practicable for lighting.

Similar microwave-induced emission can be realized if the nano-carbon with metal substrates is encased in an evacuated glass chamber. However, no emission is obtained from the carbon particles with the nonmetal substrates. So, it should not be excited directly by microwave since there is no polar molecule in relative materials. As we know, metals in a microwave oven may lead to spark or the arcing effect caused by the motion of electrons. We think the faradism in the metal with resistance heats up the nano-carbon particles. But the mechanisms how microwave excites the C_2 molecules to emit the permanent white light are still unknown since there are no polar materials in the chamber and no sparks between metal substrates and C_2 gases.

4. Summary and conclusions

In this paper, lighting systems based on nano-radiation of carbon in vacuum are demonstrated. The laser-induced white light emission from the nano-carbon is investigated in detail. It is found that the characterized nano-radiation plays the main role which often makes us confuse it with PL from nanostructured materials. Compared with other conventional white light source, smaller dimension and nice color rendering make it possible to be as a more ideal point light source in scientific experiments than laser beam, especially as a natural light point source. By applying the other practicable electromagnetic excitation, i.e. microwave excitation, permanent white light emissions are still obtained, which is caused by the faradic heating of the metal substrates with molecular C_2 spectrum besides the characterized nano-carbon radiation.

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