Carbon nanotubes for optical limiting

Jun Wang and Werner Blau

The nonlinear optical properties of dispersions of single-walled carbon nanotubes make them attractive for use in laser-protective eyewear.

In the same way that people wear sunglasses to protect their eyes from the sun’s harmful rays, those working with lasers need goggles to avoid danger from the intense beams. But conventional goggles absorb only a fixed fraction of the incident light. If the laser is bright enough, the remaining, transmitted fraction could still be dangerous. Over the last few decades, many scientists have sought so-called optical-limiting materials that strongly attenuate intense, potentially dangerous laser beams while readily transmitting low-intensity ambient light.

Several organic materials, including phthalocyanines, porphyrins, fullerene (C$_{60}$), and carbon nanotubes (CNTs), show strong nonlinear extinction (NLE) of high-intensity light and are thus candidates for practical optical limiters. Figure 1 charts the results of a search for relevant publications using the ISI Web of Knowledge.$^1$ The growing number of publications on CNTs vis-à-vis other organic materials suggests that CNT-based composites could be key optical-limiting materials in the future.

CNTs have excellent mechanical, electrical, and thermal properties, as well as attractive nonlinear optical characteristics. In contrast with the other organic materials, CNTs in dispersed form show NLE and optical-limiting effects over wavelengths ranging from the visible to the near infrared. These properties are due mainly to nonlinear scattering from bubbles of solvent and carbon vapor.$^2$ We recently investigated the nonlinear optical properties of single-walled carbon nanotubes (SWNTs) to evaluate their potential for optical-limiting applications.$^3, 4$

We distributed purified SWNTs (HiPCO, Carbon Nanotechnologies) in the amide solvents N-methyl-2-pyrrolidone (NMP), $N,N$-dimethylformamide (DMF), and $N,N$-dimethylacetamide (DMA). The open-aperture z-scan technique was employed to study the nonlinear optical properties of these SWNT dispersions.

As shown in Figure 2(a), the NLE coefficients ($\beta_{\text{eff}}$ in units of $\text{cm/W}$), which were derived from the general z-scan theory, increase enormously with rising concentration. We found that the DMF dispersions show the strongest NLE effect of the three. The optical-limiting performance is plotted in Figure 2(b) in the form of the output energy density (in units of J/cm$^2$) as a function of input energy density. This performance is also superior for DMF dispersions, and they have lower limiting thresholds.

Static light-scattering experiments revealed that the DMF dispersions have a larger scattered signal, as shown in Figure 2(c), implying that the average SWNT bundles are bigger in DMF. These results indicate that the bundle size, in combination with the physical properties of solvents, dominates the NLE and optical-limiting properties of SWNT dispersions.$^3$

We also obtained a large number of individual SWNTs by diluting with NMP. As we have demonstrated before, up to

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Figure 2. (a) Nonlinear extinction coefficients, (b) optical limiting effects, and (c) scattered intensities of dispersions of SWNTs in amide solvents NMP, DMF, and DMA.

70% of individual SWNTs are contained in NMP dispersions with concentrations of less than $4.0 \times 10^{-3}$ mg/mL. Figure 3(a) shows that the optical-limiting effects dramatically improve with increased SWNT concentration, accompanying the steady decrease of limiting thresholds, as shown in Figure 3(b). We attribute these effects to the increase in nanotube density. The individual SWNTs show an NLE effect similar to that of zinc phthalocyanine nanoparticles, and larger than molybdenum-sulfur-iodine nanowires.4

Lasers have become common in daily life and are even being incorporated into the playthings. Thus, protection from lasers is not only a scientific subject but also a potential social issue. Our

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results extend the understanding of CNTs as optical-limiting materials. However, CNTs alone could not satisfy all requirements for laser protection. We expect CNT-based complex multicomponent materials to enable practical optical-limiting devices.

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Author Information

Jun Wang and Werner Blau
The School of Physics
Trinity College Dublin
Dublin, Ireland
http://www.tcd.ie/Physics/Molecular_Electronics/pdocs/juwang.php/index.html
http://www.tcd.ie/Physics/Molecular_Electronics/
http://www.tcd.ie/Physics/Molecular_Electronics/wblau.php

Jun Wang received his PhD from the Chinese University of Hong Kong in 2006. His doctoral research was on the studies of distributed feedback waveguide lasers and microring lasers. He is currently a postdoctoral research fellow in Werner J. Blau’s group at Trinity College Dublin. His research interests include nonlinear optics of nanomaterials and polymer lasers.

Werner J. Blau is director of the Materials Ireland Polymer Research Centre at Trinity College Dublin, which encompasses researchers from the fields of physics, chemistry, engineering, and computer simulation. He has published over 390 peer-reviewed papers, edited three books, and coauthored 13 patents or applications.

References
1. The key phrases used for searching include ‘optical limiting,’ ‘phthalocyanine*,’ ‘porphyrin*,’ ‘fullerene,’ ‘carbon nanotube*’, and their combinations. Only peer-reviewed papers were included; review articles were excluded.