Polarization State Control of Light by Single-Walled Carbon Nanotubes

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Abstract: Optical activity was observed in films of vertically aligned single-walled carbon nanotubes (SWCNTs) that were grown by catalytic CVD on quartz plate. We report the control of both the polarization state and transmission of incoming light at 1550nm by azimuthal and axial tilting of SWNT film about its aligned axis.

OCIS codes: (260.5430) Polarization; (240.0310) Thin films, (060.2340) Fiber optics components

I. Introduction

Single-walled carbon nano-tubes (SWCNTs) have been the subject of focused multi-disciplinary studies due to their unique electrical, mechanical and thermal properties that could find wide applications[1]. In optical perspectives, however, SWNT applications have been very limited and applications as saturable absorbers in mode locking of erbium doped silica fiber lasers have been reported[2,3]. Control of carbon nano tube (CNT) growth direction has been recently achieved and polarization dependent optical transmission was reported at 488nm[4]. Anisotropy in thin film can be applied in effective polarization control and stretched polyethylene-terephthalate films have been used to make Feussner-type polarizers [5]. In order to meet the environment robustness, however, organic films need to be replaced by inorganic material and anisotropic carbon nano tube films would serve the purpose.

In this paper we report the optical activity of vertically aligned SWNT film in the range of 1550nm, for the first time, and polarization changes are investigated on Pointcare sphere as a function of azimuthal and axial tilt angle.

II. Experimental Results

SWCNTs were synthesized by the alcohol-CVD technique. Bimetallic Co-Mo catalyst was supported on a quartz substrate by dip-coating in an acetate solution[4]. The catalyst acetate converted into nano-scale oxide where CNT grows in vertical direction. SEM image of the grown SWNT film is shown in Fig.1-(a). Single wall structure was confirmed by Raman scattering spectra in Fig.1(b), where prominent D-band near 1590c m -1 was observed corresponding to the in-plane oscillation of carbon atoms in the graphene wall of SWCNT.

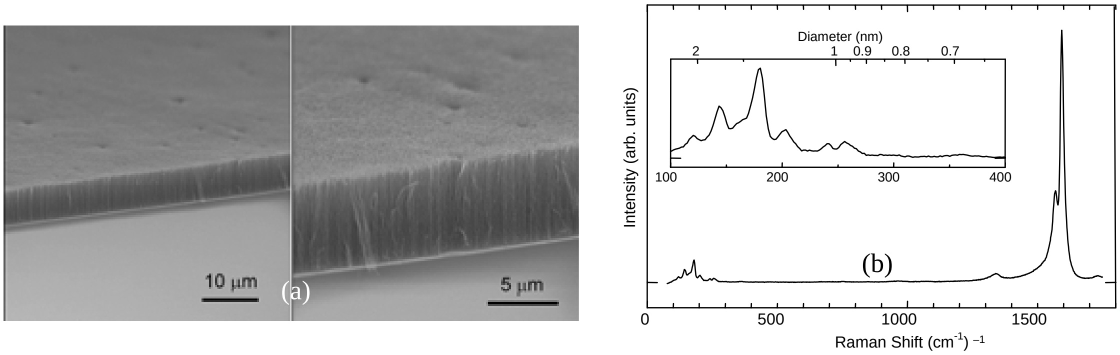

Fig.1 SEM image of SWCNTs on quartz substrate (a) and Raman spectrum at 488nm

The experimental setup for measurement of optical activity in SWNTs is shown in Fig.2. The 1550nm light emitted from a laser diode was coupled to linear polarizer (LP) to manage the state of polarization (SOP) of the input light. The optical fibers attached in LP were kept straight to prevent any perturbation in SOP of the input light. The linearly polarized input light after LP was then focused on the glass substrate coated with Carbon Nanotubes (CNTs) through a short length collimator. The substrate of CNTs was mounted on rotating stage to provide tilting in the azimuthal angle, θ, and axial angle, φ, with respect to the light propagation axis, which varies the effective interaction area between polarized input light and SWCNTs. Output light through SWCNTs was collected by another collimator and coupled to single mode optical fiber. The output polarization state of the light is then analyzed by a polarimeter (Thorlabs, PA430) along with an optical power meter. Therefore, in our setup, detailed change of SOP for various tilting angles can be traced. The power of incident light on CNTs was kept at 300μW, which is below the threshold for saturable absorption.

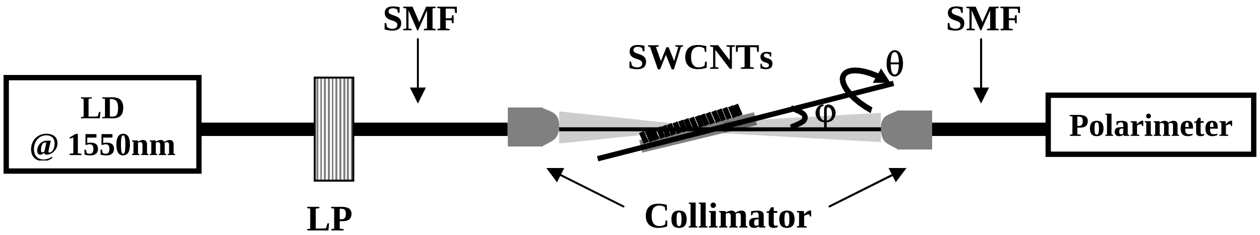

Fig. 2. Experimental setup for measuring polarization change induced by SWCNT film on quartz substrate. The substrate is mounted on a rotating stage which can provide rotating and tilting SWCNTs with azimuthal angle, θ, and axial angle, φ, respectively. ; LD: Laser Diode, LP: Linear Polarizer, SMF: Single Mode Fiber.

The change of SOP through SWCNT was measured for various tilt angle φ and corresponding traces on the Poincare sphere are shown in Fig.3-(a). The outermost circle in the figure shows SOP through a blank quartz substrate and shows the characteristics of LP used in our experiments.

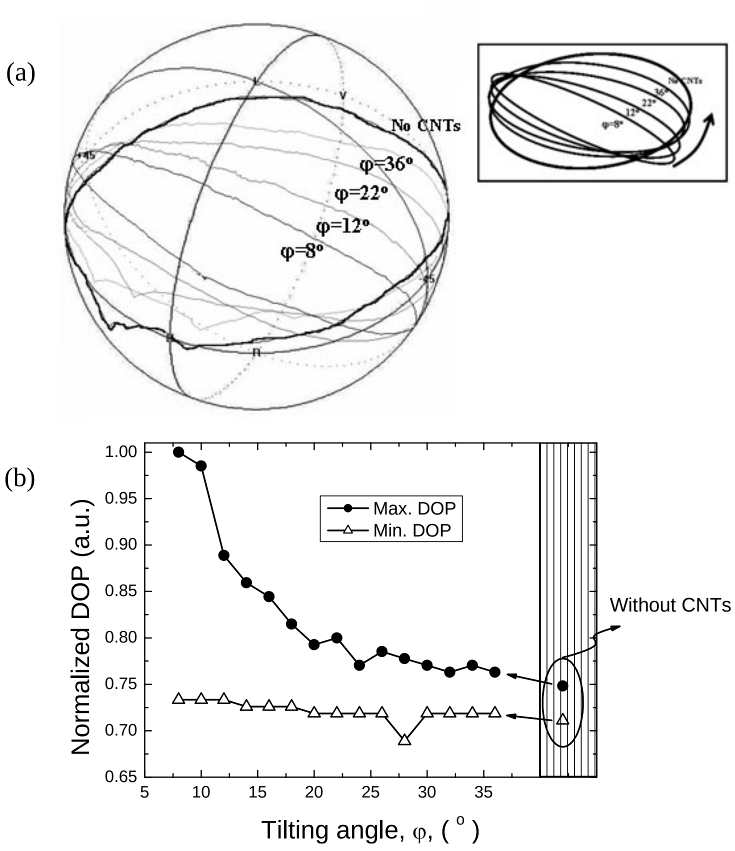

Fig. 3. (a) Traces of State of Polarization (SOP) while rotating linear polarizer with varying tilting angle, φ. The traces are illustrated in inset
(b) Degree of Polarization (DOP) depending on tilting angle of substrate. The data in shaded area were obtained without SWCNTs

For SWNT film, SOP in deed showed a significant change as the tilt angle, φ, varied, and the changes got more prominent as the substrate made a shallow angle with respect to the incident direction. This behavior is consistent with prior report observed at 488nm, where anisotropy in transmission increased for a shallower angle. In fact if φ is over 36°, we could not distinguish the traces of SWCNT from those of blank substrate. When we place CNTs with φ=8° between the collimators, it was found initially linearly polarized state changed to elliptically polarized state, which strongly indicate existence of optical activity through SWNT. Optical transmission also did depend on the tilt angle. The insertion loss of SWCNTs at φ=8° was 14.8dB and it reduced when the tilting angle increased, for example, 5.1dB at φ=25°.

The Degree of Polarization (DOP) at each tilting angle was recorded and the maximum(MAX) of DOP and minimum (Min) were plotted with normalized values in Fig. 3-(b). The DOP at each tilting angle varied within the range of Max. and Min. DOPs. As shown in Fig.3-(b), the DOPs increase in a monotonous manner with decreasing tilting angle. In particular, 40% increase in Max. DOP was observed for the tilting angle of 8° compared with blank substrate. From Fig. 3 we observed that the DOP as well as SOP were significantly affected by the interaction of SWCNT with different tilt angles. SWCNT shows semi-conductor characteristics and when vertically aligned as in Fig. 1 (a), SWCNT film will produce anisotropy in the interaction with incident plane electromagnetic wave of a linear polarization.

The SOP of output light through SWCNTs was also traced for various azimuthal angle, θ, See Fig.2, in the range of -60° <θ < 60° with keeping the tilting angle at φ=10°. As shown in Fig.4, the SOP significantly changes as a function of θ in a reproducible manner and the results manifest that the CNTs can provide a feasible solution to control polarization of light. The transverse movement of SOP in the range of 0° <θ < 40° was attributed to the incomplete alignment of CNTs in the sample. The intensity of output light through CNTs showed 180° periodicity with respect to θ such as a linear polarizing controller. The normalized intensity of output light was measured by optical power meter and the results are plotted in polar and x-y plot in Fig.5. It was found that the measured intensities showed a good agreement with $\cos^2\theta$ line in both of the plots, which has been also observed in the emission and absorption behaviors of SWCNTs [6,7].

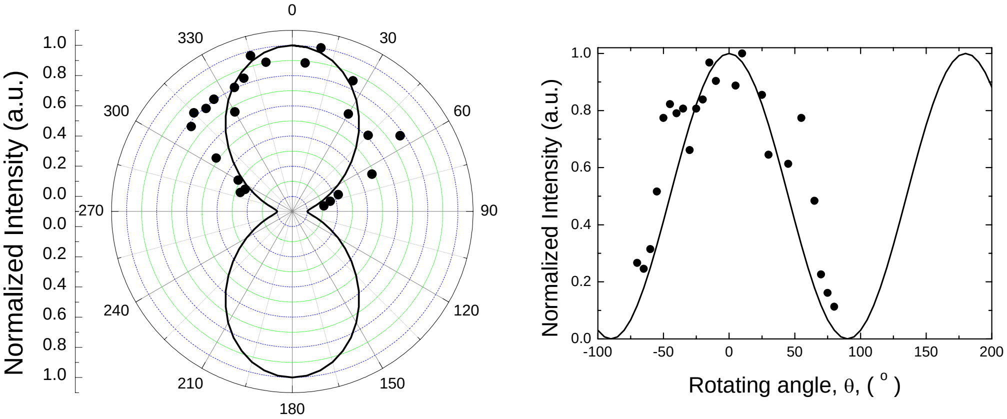

Fig. 4. Dependence of normalized intensity of output light through CNTs on the rotating angle, θ, in polar plot (a) and x-y plot (b). The lines in both of (a) and (b) are ideal $\cos^2\theta$ graphs and the circular symbols express the measured data.

III. Conclusions

In summary, by tilting a vertically aligned single-walled carbon nano tube (SWCNT) thin film we observed polarization change in terms of both the state of polarization (SOP) and the degree of polarization (DOP) in a reproducible manner. More prominent polarization change was obtained when SWCNT made a shallower angle with respect to the incident direction. In SOP linear polarization was converted to elliptic polarization, and maximum DOP increased by more than 40% at the axial angle of 8°. Output intensity also depended on azimuthal angle in $\cos^2\theta$, consistent with typical emission SWCNT.

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