Absorption Characteristics of Single Wall Carbon Nanotubes

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ABSTRACT

The different properties Carbon Nanotube (CNT) can be used for various applications. This technologically important material can be loaded into waveguides, by spray coating purified CNT or spin coated CNT – polymer composites, thus allowing the investigation of optical properties such as linear and non linear absorption characteristics, refractive index variation and the characteristics when conjugated with polymer composites.

In this paper the absorption characteristics of Carbon Nanotube is determined using SWCNT samples with varying thickness. The absorption coefficient of carbon nanotube is determined to be equal to ~24 x 10^4 cm^{-1}. The implications of such strong absorption value are discussed.

Keywords: SWCNTs, HiPCO, Absorption coefficient, saturable absorber, non linearity.

1 INTRODUCTION

Carbon Nanotubes (CNTs) [1,2] have created a lot of interest these days because of its unique optical, mechanical and electrical properties. Recently CNTs have been used for saturable absorbers and for mode- locking applications. The unique optical and electronic properties of nanotubes make them an ideal material for optical switches, modulators and saturable absorbers [12, 13]. CNTs offer a promising alternative to conventional materials such as semiconductors, polymers and optical crystals. CNTs offer practical advantages such as a simpler and lower cost fabrication process, much wider wavelength range, and can be integrated into optical systems. Although the potential field of application of CNT is increasing day by day but there are still a lot of other physical properties that need to be characterized to design photonic devices. In this paper we demonstrate the absorption characteristics of CNTs where the absorption coefficient would be investigated using experimental techniques and also the wavelength dependence of CNT over a wavelength range of 1470-1580 nm.

2 THEORY AND EXPERIMENTAL APPROACH

CNTs were investigated using experimental techniques which were based on the Lambert's - Bouguer's law. The law states that the fraction of light absorbed by a system is independent of the incident spectral radiant power and this law holds only if the incident spectral radiant power is small, and the scattering, the multiphoton processes, the excited state population and photochemical reactions are negligible. Bouguer's law therefore describes the attenuation of light where scattering is negligible. Sometimes is also called Beer-Lambert-Bouguer's law. In a medium of uniform transparency the light remaining in a collimated beam decreases exponentially with the length of the path in the medium, according to the following expressions:

$$P_o = P_{in} e^{-\alpha L} \tag{1}$$

$$ln\left(\frac{P_o}{P_{in}}\right) = -\alpha L \tag{2}$$

where P_{in} is the power input from the laser, P_o is the power output after a beam propagation length L in the sample and α is the absorption coefficient.

The objective of the present experiment is to find the absorption coefficient of Carbon Nanotube (CNT) and its wavelength dependence using the above mentioned law. A plot of the logarithm of the ratio of output power to input power as a function of CNT thickness can be used to extract the value of α.

3 GROWTH AND CHARACTERISTICS OF CNT SAMPLES

The Carbon Nanotubes used in this experiment were grown using a High Pressure Carbon Monoxide (HiPCO) process based on the Chemical Vapour Deposition (CVD) technique. The technique involves catalytic production of SWNT in a continuous flow of gas-phase CO as the source of carbon feedstock and $Fe(CO)_5$ as the iron containing catalytic precursor. The tubes used for this experiment were manufactured using the HiPCO [3,4,5] technique because this process tends to produce better SWNTs than other techniques such as Arc Discharge which contains approximately 20% soot, which would impair the characterisation of the nanotube optical properties . The HiPCO generates samples of greater purity, thus suited to our investigation.

CNT samples were produced by spraying thin films of SWNT onto a clean quartz sample having a diameter of 25 mm and a thickness of 1.5 mm. Uncoated samples were also used for control measurements and to monitor the variation of the experiment results. Additional CNT coated samples, which had lower thickness variation in the sprayed nanotube films, were also used at a later stage for verification. The nanotube thickness was measured using surface profilometry. As illustrated in table 1, the measured thickness values showed significant variations along the direction of the measurement due to the roughness of the sprayed nanotubes. Therefore an average thickness value was used for our calculations and in the plots a 15% error is shown for the sample thickness.

Surface Profilometry Measurements	Thinnest Sample (µm)	Thicker Sample (µm)	Thickest Sample (µm)
Reading 1	0.40	1.80	2.20
Reading 2	0.25	0.80	1.90
Reading 3	0.35	1.20	2.50
Average Thickness	0.333	1.26	2.20
Standard Deviation	0.076	0.50	0.33

Table 1 : Surface Profilometry readings of Carbon Nanotube thickness.

4 EXPERIMENTAL SETUP

The experimental setup used in the present work is illustrated in figure 1. The light generated by a tunable laser is passed through a 90:10 beam splitter where 10% of the light is diverted towards a power meter to monitor the optical power. The remaining light (90% of the total radiation) is passed through an optical fibre and then collimated by x16 lens, to generate a beam spot on the sample surface with a diameter of 0.5 mm. Upon transmission through the CNT [6,7] film and quartz substrate, the light beam intensity was detected using a detector. To avoid the occurrence of unpredictable spatial loss during the measurements, an infrared camera is used to check that the spot size was always smaller than the detecting area. The photodetector is connected to a calibrated power meter for measuring the transmitted power.

The experimental setup was GPIB controlled and the powers impinging on the CNT films and transmitted through it were automatically recorded. The GPIB controller is used to set the tunable laser source wavelength within the 1470-1580 nm range in steps of 1 nm with an optical power of 1 mW. Additionally, the experimental setup was shielded from ambient light in order to minimise the impact of ambient light during measurements. As explained in the section 5, calibration measurements are initially performed in order to evaluate systematic errors in the determination of the transmitted optical powers.

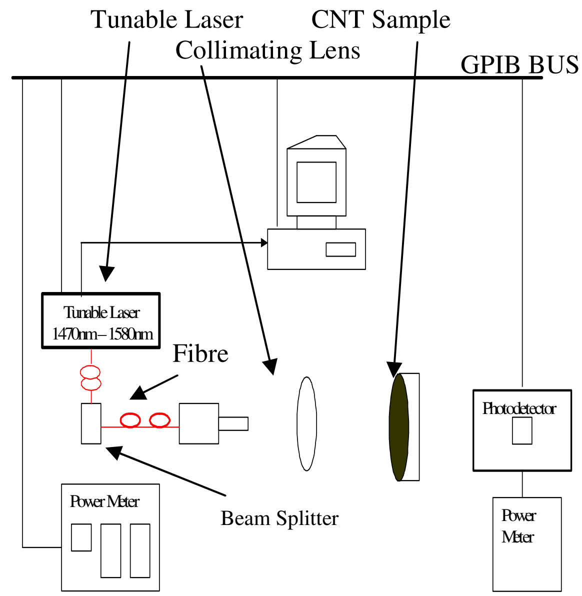

Figure 1: Experimental setup for CNT power transmission loss characterisation

5 EXPERIMENTAL RESULTS

The setup was calibrated with respect to the level of residual ambient light and the wavelength dependence of this base line was determined. The first reading was taken without any sample to measure the wavelength dependent system loss and the wavelength independent loss constant in the 1470-1580 nm range. The wavelength step used was always 1nm and the noise floor variation was in the range of 1 dB. The graph of transmission loss (without any sample) as a function of wavelength is shown in Figure 2.

Three sets of readings were taken to check the measured repeatability and the average dB reading of ($P_{out} - P_{in}$) was plotted. The system loss variation with wavelength was found taking the value of the gradient and the wavelength independent loss constant as the fit offset shown in the figure 2 below. The data was fitted using a linear fit where the slope obtained was -0.0042 dB/nm while the intercept being 5.5865 dB. The quartz loss has then been subsequently characterised and the quartz overall transmission loss was found to be 14.066dB. The 14.066 dB loss accounts for the mechanisms such as light scattering [9] at the rough surface of the CNT films, light reflection at the CNT – Quartz interface, and scattering loss through the substrate.

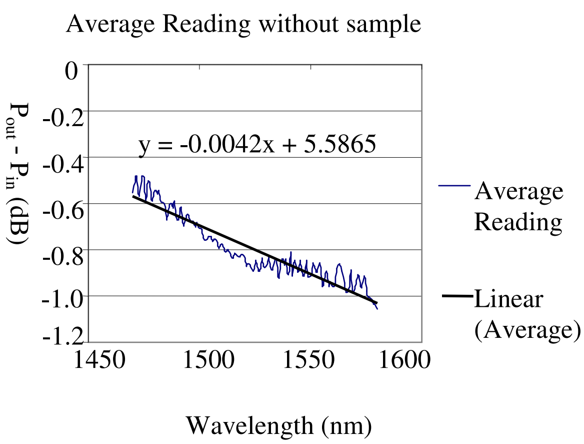

Figure 2: Determination of system loss variation and system loss constant

Finally, before proceeding to characterise the absorption coefficient, we verified that optical transmission through the sample had linear power dependence in the chosen power range of characterisation while optical nonlinearity [11] is expected at higher powers. This condition must be fulfilled in order to use the Lamberts-Bouger's Law. The figure 3 below confirms that transmission is linear for the chosen power range.

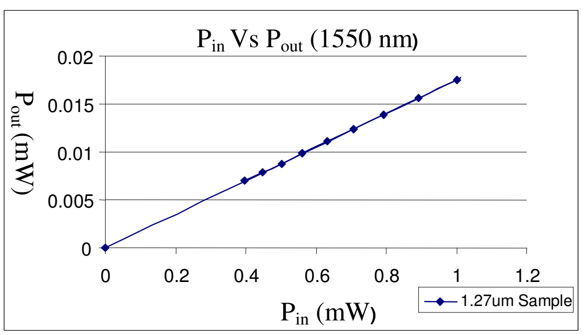

Figure 3: Linearity of the power output with input power variation.

Figure 4a and 4b compare the transmission loss through CNT/quartz without and with quartz transmission loss compensation respectively. The light transmission was characterised as function of wavelength using samples of three different CNT coating thicknesses. Each set of measurements were repeated three times to check for repeatability. Figure 4b indicates that the CNT loss transmission increases slightly with wavelength.

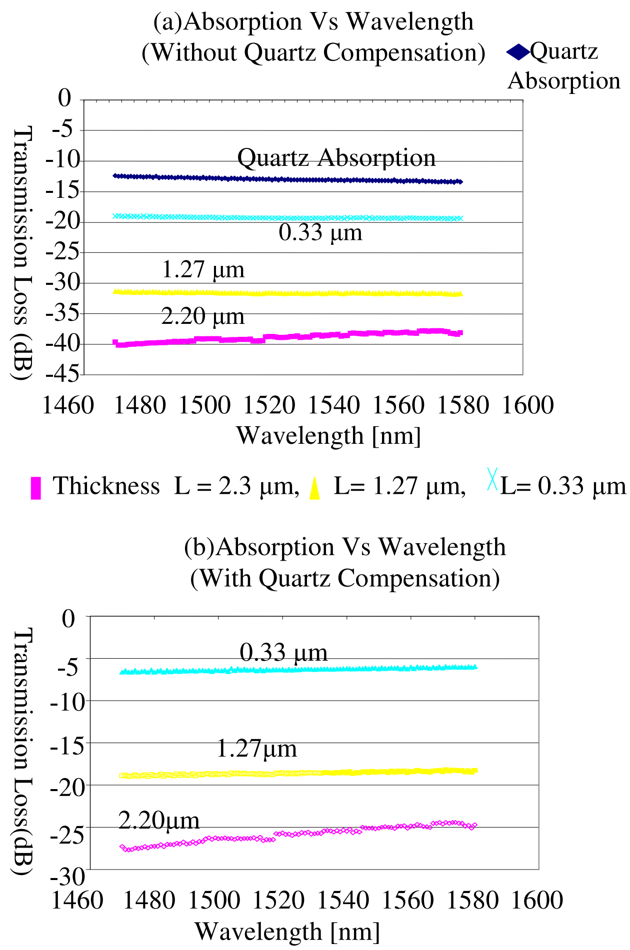

Figure 4a and b: The plot shows the absorption characteristics of CNT with wavelength variation. (a)Without quartz compensation (b) With quartz compensation

The figure. 4b indicated, for L = 2.2 um the transmission loss at 1550 nm is around -24 dB, for L= 1.27 um the loss is around -17 dB and for L= 0.33 um the loss is around -5.5 dB.

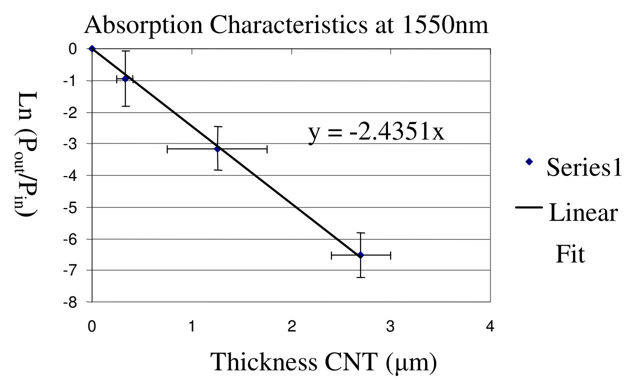

Figure 5: Linear variation of power ratio with CNT thickness.

The data acquisition software gives results in logarithm (dB) scale which were converted to power ratio of transmitted to input power. Expression (2) can be used to fit the data extracted from the measurement in figure 4b. From figure 5 a linear fit gives the slope (absorption coefficient) of the sample as ~24 x 10^4 cm^{-1}. The high absorption coefficient at these wavelengths could be due to the large number of small band gap transitions in the SWCNTs 8,9,and 10].

In order to check the absorption coefficient variation with the wavelength , values of output to input power ratios at five different wavelength were selected from the Fig 4b starting from 1470 nm to 1580 nm at 30 nm intervals for each sample thickness (L = 0.3, 1.27 and 2.7 um) and plotted in graph as shown below (Fig 6).

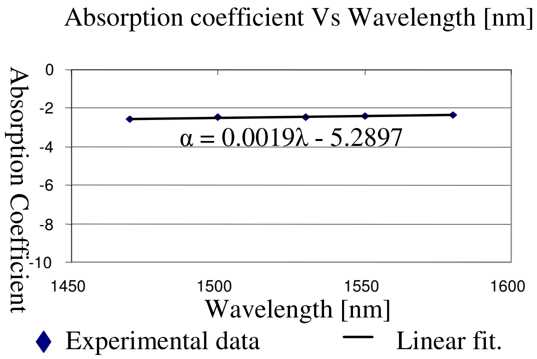

Figure 6: The variation of absorption coefficient wavelength.

The extracted absorption coefficients as a function of wavelength is plotted in figure 6. The plot shows a linear dependence of the absorption coefficient on the wavelength but, this dependence is extremely weak and is approximately equal to $d\alpha/d\lambda = 19$ cm^{-1}/nm.

6 CONCLUSION

Our studies indicate that SWCNTs are a highly absorptive material with an absorption coefficient of ~24 x 10^{-4} cm^{-1}. The measurement variation in the CNT thickness has been taken into consideration when analysing the results. Our studies indicate that Single Walled Carbon Nanotubes have a very high absorption coefficient, but very weak dependence over the investigated range of wavelength (1470 – 1580 nm). This implies that only very thin films of CNT can be used in photonic applications, alternatively a method must be devised for diluting CNT in a hosting material like a polymer. As CNTs have very weak wavelength dependence in the 1470-1580 nm range they appear well suited for telecommunication applications at around 1550 nm. If we can confirm that optical non-linearities in CNTs are stronger than in standard semi-conducting material, we will have a very high performance material that would provide all the non - linear effects over a wavelength range unmatched by any other existing semiconducting material. So it is crucial to investigate and characterise the non-linear optical characteristics of CNT based material. CNTs can be used in many potential devices such as waveguides, mode-locked lasers using saturable absorber and many other potential applications.

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