X-ray propagation in multiwall carbon nanotubes

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Structure of presentation

• Motivation for and background to the research
• Waveguiding in CNTs
• Reflectivity and x-ray modes in multiwall CNTs
• Bragg scattering and x-ray modes in coated multiwall CNTs
• Optimisation of Bragg structure
• Fabrication of CNTs for waveguiding
• Conclusions
Motivation

• Semiconductor manufacturing is a multi-billion dollar industry.

• Nanoscale lithography will be very expensive.

• New photolithography tools are required for the fabrication of devices having nanometre scale dimensions.

• New characterisation tools are required.

• X-ray propagation in carbon nanotubes has the potential to provide a substantially cheaper alternative.
Background

- Possibility of channelling by neutral particles in carbon nanotubes postulated by Zhevago and Glebov (1998)

- Coherent propagation of x-rays demonstrated in a planar waveguide, Zwanenburg et.al. (1999)

- Recent demonstration of the growth of regular arrays of carbon nanotubes, Milne (Cambridge) and others.
Applications

X-rays

X-ray lithography

Photoelectron spectroscopy

XPS
Structure of waveguide

- Highly absorptive coating
- SiO$_2$
- Carbon nanotubes
- X-ray transmission
**X-ray scattering at an interface**

Reflection and field penetration of x-rays at an interface

Total external reflection occurs when $\theta < \theta_C$

And the critical angle $\theta_C$ is

$$\theta_C = \sqrt{2\delta} \sim \text{mrad}$$

$$\delta = \frac{n_a r_e \lambda^2}{2\pi} f_1^0(\omega)$$

$$\beta = \ldots \ldots f_2^0(\omega)$$

penetration depth, $d_0 \sim 6.4\text{nm}$ in carbon
Propagation of x-rays in a planar waveguide

Field penetration depth, \( d_0 \) is given by

\[
d_0 = \frac{\lambda}{2\pi\sqrt{2\delta}} = \frac{1}{2\sqrt{n_a r_e \pi f_1^0}} = 6.4nm \quad (\text{carbon, atomic number, } Z=6)
\]
Propagation of x-rays in a planar waveguide

Field penetration depth, $z_0$ is given by

$$d_0 = \frac{\lambda}{2\pi\sqrt{2\delta}} = \frac{1}{2\sqrt{n_a r_e \pi f_1^0}} = 6.4\text{nm}$$ (carbon, atomic number, $Z=6$)

$$d_0 >> \text{thickness of nanotube wall} \sim 0.1\text{nm}$$
Coating of CNT’s demonstrated

Well ordered vertical nanotubes coated with polypyrrole

Coating thickness 93 nm on carbon nanotubes
with diameter ~ 30 nm
Propagation of x-rays in CNT’s analogous to fibre optics

Refractive index, $n$, of coating (cladding) = $1 - \delta$ \quad (\delta \sim 10^{-4})
Low order modes in a coated CNT

Normalized transverse wavevector $= k_{L} a / V$

$V = k_{0} a (n_{\text{core}}^{2} - n_{\text{clad}}^{2})^{1/2} = a / d_{0}$
Multiwall CNT

A Loiseau et. al, Understanding Carbon Nanotubes: From Basics to Applications
2006: Springer; 1st Edition
Growth of CNT’s
Propagation of x-rays in CNT’s analogous to fibre optics

Refractive index, \( n \), of coating (cladding) = 1 - \( \delta \) \( (\delta \sim 10^{-4}) \)
Simulation of propagation must take account of the Multiple walls

Reflectivity from 15 layers of C/Air as a function of incident angle and wavelength
Reflectivity from 15 layers of C/Air as a function of incident angle and wavelength

15 layers of carbon and air, $d_c = 0.8 \times 10^{-10} \text{m}$, $d_{air} = 3.34 \times 10^{-10} \text{m}$
EM mode formed in a MWNT (7 walls) coated with gold
CNTs coated with WS$_2$

HRTEM images of a MWCN coated with a) single and b) double layer of WS$_2$. Scale bars=5nm

R L D Whitby et. al., Chemphyschem (2001) No 10 p.620
Reflectivity from 50 layers W/Air (2.52Å/6.2Å) on C/Air

Reflectivity with $\lambda \approx 0.5\,\text{Å}$ and $\theta \approx 1.5\,^\circ$ is about 6% with $\lambda \approx 2\,\text{Å}$ and $\theta \approx 6.5\,^\circ$ is about 5%
Structure of Bragg fibre

Radial component of the magnetic field, 50 nm radius nanotube coated with W/Air (2.52Å/6.2Å)

\[ \beta = 3.1207 e^{10} - 2.19 e^{i6i}, \lambda = 2 e^{010}, n_{eff} = 0.99334 - 6.9921 e^{005i} \]
Reflectivity from 50 layers of W/Air (11.08Å/25.84Å)

50 layers of tungsten and air

d_{w} = 11.076 \times 10^{-10} \text{ m,}

d_{air} = 25.844 \times 10^{-10} \text{ m}

\lambda = 0.4 \text{ nm}
\lambda = 0.6 \text{ nm}
\lambda = 0.8 \text{ nm}
\lambda = 1.0 \text{ nm}
\lambda = 1.2 \text{ nm}
Radial component of magnetic field at a wavelength of 7.5Å for 50 layers of W/Air (11.08Å/25.84Å)
Modes established by Bragg scattering in MWNT coated with 50 layers of W/Air
Conclusions

• Modelling suggests that x-ray propagation is feasible

• Multiwall CNTs have inherent Bragg structure but reflectivity is weak

• Coated CNTs offer potential as Bragg fibres but many layers required for strong reflectivity

• Need experimental verification of x-ray propagation