Modeling of multiwalled carbon nanotubes based metamaterials and photonic crystals

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Abstract—**Highly dense periodic arrays of multiwalled carbon nanotubes can be utilized as sub-wavelength structures for metamaterials and photonic crystals. We have established a metamaterial structure which acts as a plasmonic high pass filter using a 400nm spacing nanotube array and also utilized its band-gaps to construct photonic crystals based waveguides and switches.**

Keywords-component; periodic arrays of multiwalled carbon nanotubes; metamaterials; photonic crystals; optical waveguides and swictches

I. INTRODUCTION

Multiwalled carbon nanotubes (MWCNTs) since their discovery by Iijima have been the focus of extensive research. Two-dimensional periodic arrays of vertically aligned MWCNTs can be grown at precisely determined locations by plasma-enhanced chemical vapor deposition (PECVD). They present great potential for applications requiring periodic metallic structures and dielectric function, such as nano-antennas, metamaterials and photonic crystals. In this manuscript we present the utilization of 2D periodic arrays of MWCNTs as sub-wavelength structures for constructing very interesting plasmonic and photonics devices, i.e. metamaterials and photonic crystals. These devices utilize the optical properties of individual CNTs to display interesting plasmonic filtering effects and perform effective wave guiding/switching in the optical regime.

II. MWCNT BASED METAMATERIALS

Metamaterials can be formed artificially by sub-wavelength components to display properties beyond those available in naturally occurring materials. It has been reported by Pendry et al. [1] that the periodic arrays of thin metal wire structures, excited by an electric field parallel to the wires, act as metamaterials and display plasmonic response in the frequency domains depending on the array geometry. They demonstrate plasma frequencies which are much lower than in the metal structures and can be utilized for filtering in microwave and terahertz frequency domains. Here we demonstrate that two-dimensional high density arrays of metallic MWCNTs (metallic nano-wire structures) can be used to realize such plasmonic filters which operate in the optical regime.

Highly dense array of MWCNTs, excited by an electric field parallel to the wires, will perform similar to a low-density plasma of very heavy charged particles, with a plasma frequency $\omega_{p,}$ given by

$$\omega_p^2 = (2\pi c_0^2)/(a^2 \ln(a/r)) \qquad (1)$$

where c_0 is the velocity of light in vacuum, a is the lattice constant of the 2D MWCNT array and r is the radius of the nanotubes. The lowering of the plasma frequency is due to the increase in the effective electronic mass on the nanotubes due to the induced current and corresponding magnetic field around them. According to (1), the effective plasma frequency strongly depends on the nanotube radius and lattice constant. Their values can be discretely chosen to engineer the MWCNT arrays of the desired plasma frequency.

The resultant frequency dependent permittivity of the metamaterial can be calculated using the Drude model for metals, which shows that the effective permittivity $\varepsilon(\omega)$ is negative for frequencies less than ω_p, therefore no wave propagation will take place inside the metamaterial. Electromagnetic waves propagation only occurs above ω_p, due to which the structure acts as a nanotube based nanophotonic high-pass filter.

Theoretical study, using (1), showed that a square lattice MWCNT array, with a = 400 nm and r = 50 nm, displays a plasma frequency $f_p = \omega_p/2\pi$ of 207.5 THz (λ_p of 1.44 μm). To confirm the filtering effect a Finite Element Method modeling of the same MWCNT array was performed using the "*RF Waves"* application mode of COMSOL Multiphysics® to study the propagation of optical/terahertz waves through it. The dielectric properties of individual MWCNTs were obtained from reference [2].

The modeled geometry and simulated results for the Transverse Electric (TE) mode propagation (incident electric field parallel to the nanotubes) are presented in Fig. 1. The results show that the MWCNT array allowed transmission to the waves having wavelengths of about 1 μm and less. The wavelengths above 1.25 μm were completely reflected showing that the high density MWCNT array displayed a plasmonic filtering effect for a plasmonic wavelength λ_p of about 1.25 μm, which is in close proximity to the plasmon wavelength λ_p of 1.44 μm calculated using (1). The mismatch can be explained by the difference in the dielectric properties used.

The fabrication of the MWCNT based high pass filter was also performed and a scanning electron microscope (SEM) image is shown in Fig. 1 (a). The growth of such high *a/r* aspect ratio array was a difficult task. The characterization

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Haider Butt specially thanks Professor Gehan Amaratunga, Cambridge Commonwealth Trust (CCT) and Hughes Hall College for granting the funding to pursue this research.

results for the MCWNCT array based plasmonic filter showed a good match with the calculated results and will be published elsewhere.

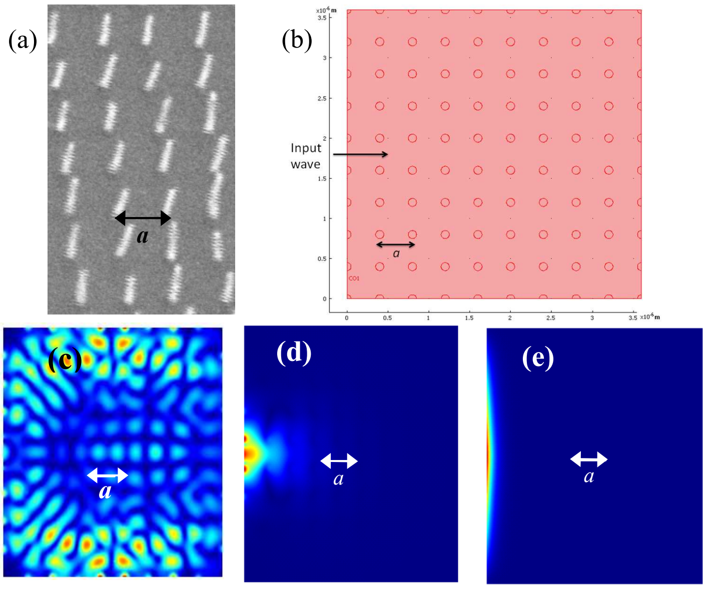


Figure 1. (a) SEM image of a 2D MWCNT array with tube radius of 50 nm and lattice constant *a* of 400 nm, grown on silicon substrate using PECVD after employing e-beam lithography to pattern a 5 nm thick nickel catalyst dots. (b) TE modeling of the same with incident wave from the left. Wavelengths of (c) 0.5 um and (d) 1 um propagate into the array. After a cut-off wavelength of (e) 1.25 um all the waves are reflected by the metamaterial.

III. PHOTONIC CRYSTALS BASED WAVEGUIDES & SWITCHES

Periodic arrays of MWCNTs have shown to act as photonic crystals [3]. The dielectric periodicity in the arrays gives rise to the Bragg-scattering of the propagating electromagnetic waves and also to the opening of energy band gaps. No real wave vector exists for any mode at the frequencies belonging to the band gap, however, by placing defects in the array these modes can be guided without significant loss. To demonstrate this photonic wave guiding effect we modeled and fabricated a 2D MWCNT array (with tube radius 50 nm and lattice constant 400 nm) having 800 nm wide line defects. Fig. 2 displays the simulated result for the propagation of a wave having 800 nm wavelength through the line defect. The fabricated MWCNT based waveguide structure is also shown in Fig. 2 (c).

Similarly, wavelength switching can also be achieved by introducing multiple line defects with varying dimensions in the MWNT based photonic crystals. Only the frequency modes having their wavelengths comparable to the line defect dimensions are able to propagate through them. Modeled results demonstrated the switching of wavelengths as shown in Fig. 3.

IV. CONCLUSION

Our results demonstrate that the periodic arrays of MWCNTs promise great potential towards the nano-scale photonic devices which can be utilized for optical filtering, wave guiding, switching and wavelength multiplexing.

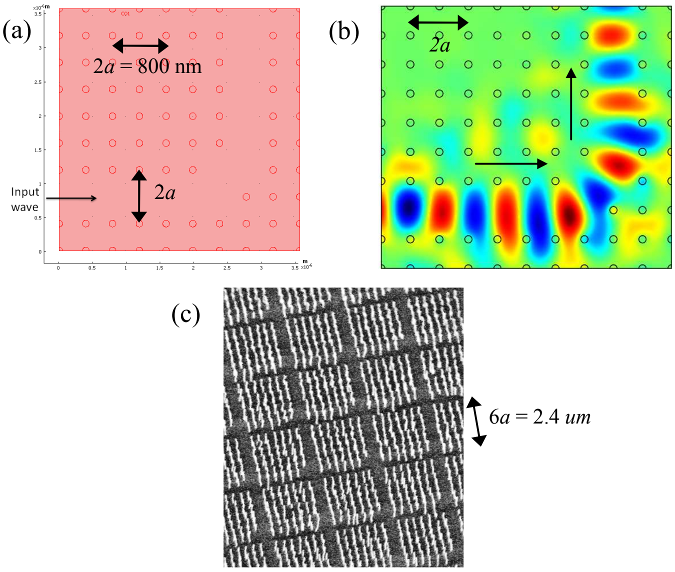


Figure 2. (a) Modeled MWCNT based photonic waveguide, with a line defect of 2*a* = 800 nm and tube radius = 50 nm. (b) Simulated (TE mode) propagation of a 800 nm wavelength wave through the line defect. (c) SEM image of the fabricated MWCNT based waveguide; the line defects in the array are visible.

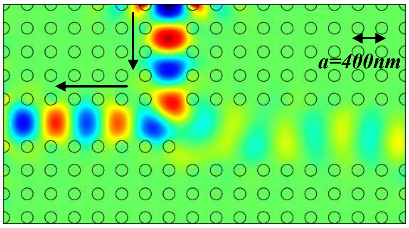
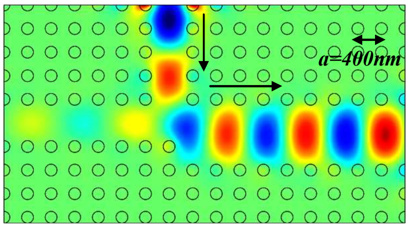
(a) An incident wave (from the top), of wavelength 810 nm, propagates through the left line defect, having a width of 2*a* =800nm.	
(b) Incident wave (from the top), of wavelength 1160 nm, propagates through the right line defect (width 3*a*=1200 nm).	

Figure 3. MWCNT based 2D photonic crystal wavelength switch. Incident waves (from the top) of lower wavelengths are deflected to the left and higher wavelengths are deflected to the right. The figure shows the simulated TE mode propagation of (a) λ= 810 nm and (b) λ=1160 nm. The lattice constant of MWCNT array is 400nm.

REFERENCES

[1] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Low frequency plasmons in thin-wire structures," Journal of Physics: Condensed Matter, vol. 10, pp. 4785-4809, 1998.

[2] F. Bommelia, L. Degiorgia, P. Wachtera, W. S. Bacsab, W. A. d. Heerb, and L. Forroc, "Evidence of anisotropic metallic behaviour in the optical properties of carbon nanotubes," Solid State Communications, vol. 99, pp. Pages 513-517 1996.

[3] K. Kempa, B. Kimball, J. Rybczynski, Z. P. Huang, P. F. Wu, and D. Steeves, "Photonic Crystals Based on Periodic Arrays of Aligned Carbon Nanotubes," Nano Letters, vol. 3, pp. 13-18, 2002.