Optical waveguides and switches based on periodic arrays of carbon nanotubes

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Abstract—**This document presents the modeling and characterization of novel optical devices based on periodic arrays of multiwalled carbon nanotubes. Vertically aligned carbon nanotubes can be grown in the arrangement of two-dimensional arrays of precisely determined dimensions. Having their dimensions comparable to the wavelength of light makes carbon nanotubes good candidates for utilization in nano-scale optical devices. We report that highly dense periodic arrays of multiwalled carbon nanotubes can be utilized as sub-wavelength structures for establishing advanced optical materials, such as metamaterials and photonic crystals. We demonstrate that when carbon nanotubes are grown close together at spacing of the order of few hundred nanometers, they display artificial optical properties towards the incident light, acting as metamaterials. By utilizing these properties we have established micro-scaled plasmonic high pass filter which operates in the optical domain. Highly dense arrays of multiwalled also offer a periodic dielectric constant to the incident light and display interesting photonic band gaps, which are frequency domains within which on wave propagation can take place. We have utilized these band gaps displayed by a periodic nanotube array, having 400 nm spacing, to construct photonic crystals based optical waveguides and switches.**

Keywords-carbon nanotubes; periodic arrays, photonic crystals; optical waveguides; switches;

I. INTRODUCTION

Carbon nanotubes first discovered by S. Iijima in 1991 [1] are very promising materials and have been the focus of enormous research. Two main types of carbon nanotube exist in stable states, single walled carbon nanotubes (SWCNTs) and multiwalled carbon nanotubes (MWCNTs) [2]. SWCNTs are structurally similar to a single graphite sheet wrapped into a cylindrical tube and MWCNTs comprise an array of such tubes concentrically nested like the rings of a tree trunk. SWNTs can be either metallic or semiconducting, depending on the direction about which the graphite sheet is rolled to form a nanotube cylinder. MWCNTs on the other hand are mostly metallic and are able to carry high current densities. Due to their high conductivities and aspect ratios they produce very strong electric fields, which make them an efficient source of electrons, as has been demonstrated in field emission displays [3]. Arrays of MWCNTs have been used as electrodes in rectifiers and other electrical devices [4], solar cells to increase the efficiency, optical antenna arrays and photonic crystals [5].

MWCNTs are normally grown as tangled masses by laser ablation or arc discharge. However, for most devices nanotubes with well defined diameters and lengths are required. The exact positioning of the nanotubes is also vital for proper functioning of many devices. Two-dimensional periodic arrays of vertically aligned MWCNTs can be grown at precisely determined locations by the process of plasma-enhanced chemical vapour deposition (PECVD) [6, 7]. Amongst the many methods used for the growth of carbon nanotubes, PECVD has the advantage of being controllable. Vertically aligned arrays of MWCNTs can be grown on silicon substrates, from plasma, after employing e-beam lithography to deposit a nickel catalyst layer. Under suitable conditions of temperature, pressure and gas concentration [8] the nanotubes of required sizes are grown only at the positions defined by the nickel catalyst, giving precise control of the position and geometry of the nanotube arrays. The diameter and length of the MWCNTs is controlled by the diameter of the nickel catalyst dots and the running time of the PECVD process respectively. Therefore, periodic arrays of carbon nanotubes of any dimensions and periodicity can be fabrication for their applications in electrical and optical devices.

In this manuscript we present the utilization of 2D periodic arrays of MWCNTs as sub-wavelength structures for constructing very interesting plasmonic and optical devices, i.e. metamaterials and photonic crystals. We have studied very interesting optical effects in highly dense arrays of nanotubes. When nanotubes are grown close together, with spacing of about 400 nm and radius 50 nm, they display artificial physical properties not existing in nature, acting as metamaterials. The effective electronic mass on the nanotubes changes, due to mutual coupling between them and they start displaying dielectric properties which are inherently different from their own. We present an optical high pass filtering application of carbon nanotube based metamaterials. Some promising modeling and experimental results are demonstrated showing a strong cut-off filtering effect at the plasma frequency displayed by the periodic arrays of multiwalled carbon nanotubes.

In addition, we present that the dielectric periodicity, displayed by the periodic arrays of MWCNTs, can be utilised for producing photonic crystals. Our modelling results suggest that MWCNTs based photonic crystals can be used for interesting applications like optical wave guiding, beam splitting and wavelength multiplexing at micron-scale. Due to the advancement in nanotechnology such photonics crystals are becoming simpler to fabricate and propose great potential as future applications. We have also carried out the fabrication of these promising devices and obtained some fascinating scanning electron microscopy (SEM) images of these nano-scale applications.

II. MWCNT BASED METAMATERIALS

The 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. [9] 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 act like a low-density plasma of very heavy charged particles, with a plasma frequency ω_p, given by

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

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 [10].

The model geometry and simulated results for incident electric field parallel to the nanotubes (TE mode) 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.

After confirming the filtering effect through the modeling results, fabrication of MWCNT based high pass filter was performed. 2D array of MWCNTs, with tube interspacing of 400 nm and radius of 50 nm, was fabricated on silicon substrate using the PECVD process. SEM images of the grown nanotube samples are shown in Fig. 2. The growth of such high *a/r* aspect ratio array was a difficult task, overcome through e-beam lithography and optimized growth recipe. CNT arrays displaying good periodicity and alignment were obtained. Optical characterization of the obtained samples was performed using white light source at an incident angle of 60° and very promising results were obtained. The experimental results for the MWCNTs based plasmonic filter showed a good match with the calculated results and were published in a reputable journal [12].

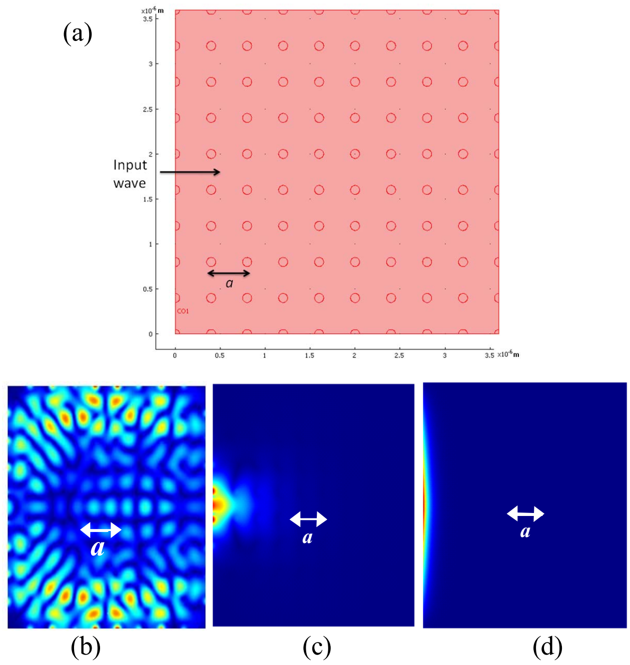


Figure 1. (a) TE modeling of the 2D MWCNT array, having radius of 50 nm and lattice constant *a* of 400 nm, with incident wave from the left. Wavelengths of (c) 0.5 um and (d) 1 um propagate into the array. After a cut-off wavelength of (e) 1.25 um all the waves are reflected [11]

III. PHOTONIC CRYSTALS BASED WAVEGUIDES & SWITCHES

A. Photonic crystal waveguides

Photonic crystals (PCs) are interesting materials which present periodicity in their dielectric constant. Bragg scattering occurs when the periodicity of the dielectric constant is comparable to the wavelength of the incident electromagnetic waves. This introduces band gaps, which means the electromagnetic waves falling in these bands are not able to propagate through the PCs.

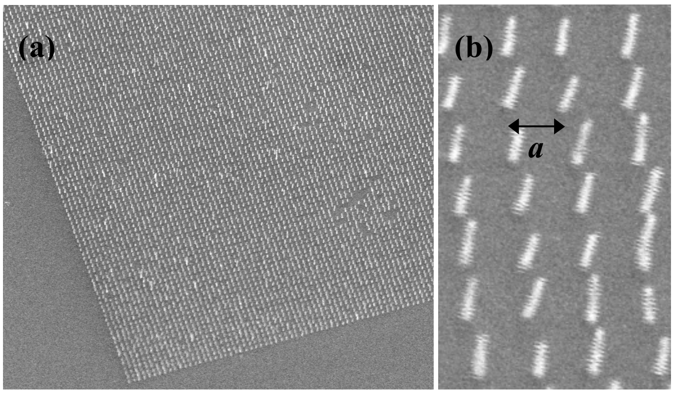


Figure 2. (a) SEM image of the fabricated 2D array of MWCNTs with tube radius of 50 nm and a=400 nm, grown on silicon substrate using PECVD after employing e-beam lithography to pattern a 5 nm thick nickel catalyst dots. (b) A magnified version of the same.

If these band gaps fall in the optical frequency range they are called photonic band gaps. The band gaps displayed by the PC allow them to effectively influence the propagation light and pave way towards their utilization in various interesting photonic devices. Periodic arrays of MWCNTs have been shown to act as photonic crystals [5]. 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.

By removing a row of MWCNTs from the array a line defect can be introduced, within which the light can propagate without escaping into the lattice. By using this effect, very efficient photonic crystal waveguides (with sharp bends) can be established at micron-scale. To demonstrate this photonic waveguide affect we modeled a 2D array of MWCNTs (with tube radius 50 nm and lattice constant 400 nm) having a 800 nm wide line defect. The line defect with a sharp 90^{o} bend was introduced in the 2D lattice and the optical wave propagation through it was analyzed. Fig. 3 displays the simulated result for the propagation of a 800 nm wavelength wave through the line defect. The optical waves propagate through the sharp turn waveguide without much loss and do not travel out of the defect into the lattice because their frequency lies within the band gap and decay away from the defect. The result is of interest here as this wave guiding phenomenon can be further utilized for effective optical switching and wavelength multiplexing at micron-scale. The fabrication of MWCNT based waveguide structures was also performed and the SEM image of the fabricated array of waveguides is shown in Fig. 3(c).

B. Optical Switches

Having established the photonic crystal waveguides, a variety of passive applications like optical dividers, switches, multiplexers, and ring resonators can be constructed by appropriately designing the line defects in the MWCNT arrays. Photonic crystals based wavelength switching can be achieved by introducing multiple line defects of varying dimensions within the MWNT arrays. Only the frequency modes having their wavelengths comparable to the line defect dimensions are able to propagate through them. A MWCNTs based optical switch was modeled consisting of two line defects, 800 nm and 1200 nm wide. Only the waves with wavelengths comparable to the line defects were able to propagate through them, as shown in Fig. 4.

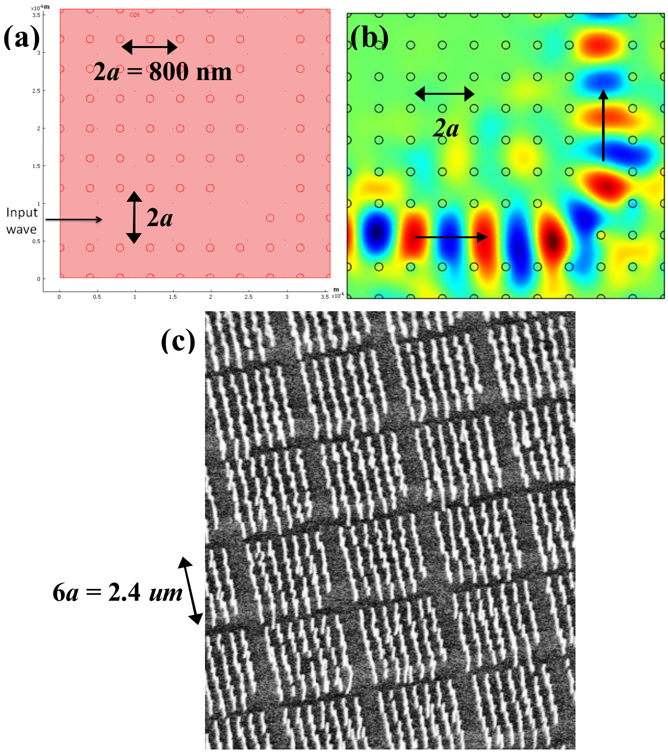
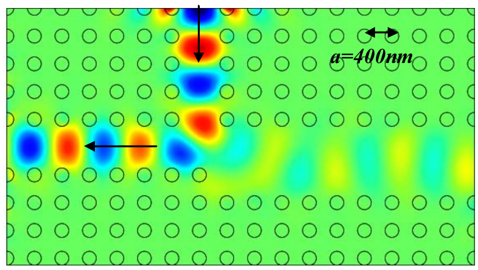


Figure 3. (a) Modeled MWCNT based optical waveguide, with a line defect of 2a = 800 nm and tube radius = 50 nm. (b) Simulated (TE mode) propagation of a 800 nm wavelength wave through the 90o turn waveguide. (c) SEM image of the fabricated MWCNT based waveguides; the line defects in the array are visible [11].

(a) An incident wave (from the top), of wavelength 810 nm, propagates through the left line defect, having a width of 2a =800nm.



(b) Incident wave (from the top), of wavelength 1160 nm, propagates through the right line defect (width 3a=1200 nm).

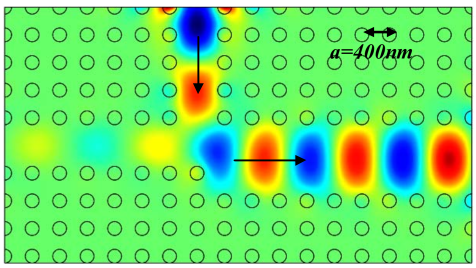


Figure 4. Modeled MWCNT based optical switch. Incident wave (from the top) of smaller wavelength, (a) 810 μm, propagates in the narrow line defect on the left and a larger wavelength, (b) 1.25 μm moves into larger line defect on the right, showing the concept of beam splitting [11].

The results show that by using periodic arrays of multiwalled carbon nanotubes, highly efficient optical switching can be achieved for devices with micro-scale dimensions.

IV. CONCLUSION

In this manuscript we present the utilization of 2D periodic arrays of MWCNTs as sub-wavelength structures for constructing very interesting plasmonic and optical devices, i.e. metamaterials and photonic crystals. High density arrays of nanotubes (with interspacing of 400 nm) act as metamaterials, displaying plasmonic cut-off filtering effect in the optical domain. Such arrays also display band gaps which pave way towards their utilization as optical waveguides and switches. Our results demonstrate that the periodic arrays of MWCNTs promise great potential towards the micron-scale photonic devices which can be utilized for optical filtering, wave guiding, switching and wavelength multiplexing.

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REFERENCES

[1] S. Iijima, "Helical microtubules of graphitic carbon," Nature, vol. 354, pp. 56-58, 1991.

[2] R. H. Baughman, A. A. Zakhidov, and W. A. de Heer, "Carbon Nanotubes--the Route Toward Applications," Science, vol. 297, pp. 787-792, August 2, 2002 2002.

[3] C. Deuk-Seok, S. H. Park, H. W. Lee, J. H. Choi, S. N. Cha, J. W. Kim, J. E. Jang, K. W. Min, S. H. Cho, M. J. Yoon, J. S. Lee, C. K. Lee, J. H. Yoo, K. Jong-Min, J. E. Jung, Y. W. Jin, Y. J. Park, and J. B. You, "Carbon nanotube electron emitters with a gated structure using backside exposure processes," Applied Physics Letters, vol. 80, pp. 4045-4047, 2002.

[4] Y. Chen, C. Liu, and Y. Tzeng, "Carbon-nanotube cold cathodes as non-contact electrical couplers," Diamond and Related Materials, vol. 12, pp. 1723-1728, 2003.

[5] K. Kempa, B. Kimball, J. Rybczynski, Z. P. Huang, P. F. Wu, D. Steeves, M. Sennett, M. Giersig, D. V. G. L. N. Rao, D. L. Carnahan, D. Z. Wang, J. Y. Lao, W. Z. Li, and Z. F. Ren, "Photonic Crystals Based on Periodic Arrays of Aligned Carbon Nanotubes," Nano Letters, vol. 3, pp. 13-18, 2002.

[6] K. B. K. Teo, M. Chhowalla, G. A. J. Amaratunga, W. I. Milne, D. G. Hasko, G. Pirio, P. Legagneux, F. Wyczisk, and D. Pribat, "Uniform patterned growth of carbon nanotubes without surface carbon," Applied Physics Letters, vol. 79, pp. 1534-1536, 2001.

[7] M. Chhowalla, K. B. K. Teo, C. Ducati, N. L. Rupesinghe, G. A. J. Amaratunga, A. C. Ferrari, D. Roy, J. Robertson, and W. I. Milne, "Growth process conditions of vertically aligned carbon nanotubes using plasma enhanced chemical vapor deposition," Journal of Applied Physics, vol. 90, pp. 5308-5317, 2001.

[8] T. D. Wilkinson, X. Wang, K. B. K. Teo, and W. I. Milne, "Sparse Multiwall Carbon Nanotube Electrode Arrays for Liquid-Crystal Photonic Devices," Advanced Materials, vol. 20, pp. 363-366, 2008.

[9] 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.

[10] 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.

[11] H. Butt, Q.Dai, P. Farah, R. R., K. Won, T. D. Wilkinson, and G. A. J. Amaratunga, "Modeling of multiwalled carbon nanotubes based metamaterials and photonic crystals," in 15th European Conference on Integrated Optics (ECIO) Cambridge, United Kingdom, 2010.

[12] H. Butt, Q.Dai, P. Farah, T. Butler, T. D. Wilkinson, J. J. Baumberg, and G. A. J. Amaratunga, "Metamaterial high pass filter based on periodic arrays of multiwalled carbon nanotubes," Applied Physics Letters, vol. 97, 2010 (in press).