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Numerical simulation of polarization beam splitter with triangular lattice of multi-walled carbon nanotube arrays

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ABSTRACT

A kind of polarization beam splitter with triangular lattice of multi-walled carbon nanotube arrays is designed and simulated. In the employed structure transverse-electric (TE) light is confined in the line defect with photonic band gap effect, while transverse-magnetic (TM) light is guided through it with extremely low diffraction. The performance of the designed polarization beam splitter is evaluated by utilizing optical properties of multi-walled carbon nanotubes, finite element modeling of wave propagation and transmission through periodic arrays. Simulation results indicate that the designed polarization beam splitter has low loss and less cross talk, and thereby may have practical applications in the integrated optical field.

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1. Introduction

Carbon nanotubes (CNTs) have been the focus of extensive nanotechnology research since they were reported by Iijima in 1991 [1]. Along with the continuous improvement of skillful engineering they have been desirable candidates for a myriad of potential applications and devices [2,3] because of their optical and electrical properties. CNTs are very complicated materials including strongly anisotropic [4–8] and highly nonlinear [9–12]. There are two representative types of CNTs which exist in stable states, single-walled carbon nanotubes (SWCNTs) containing of a single rolled-up graphene layer, and multi-walled carbon nanotubes (MWCNTs) having two or more layers. Depending on the direction about which the graphene sheet is rolled to form CNT, the nanotubes can behave as metallic or semiconducting. Interesting optical properties as well as excellent electrical features of carbon nanotubes combining with regular array structure have been demonstrated for fascinating applications such as electrodes [13,14], gas sensors [15,16], and optical antenna arrays [17–19]. It was reported that periodic arrays of CNT could serve as photonic crystals (PCs) [20–22] which were testified for many important effects and applications with a spatial periodicity in dielectric constant. In terms of MWCNT-based photonic crystals, however, little has been done. Multi-walled carbon nanotubes are mostly metallic and are able to carry high current densities, in addition to their nanoscale dimensions comparable to the wavelength of light, therefore, the photonic properties of the MWCNT arrays have attracted numerous attentions which are very similar to those of bulk graphite [9,23,24].

In this study, the radio frequency (RF) module of COMSOL Multiphysics based on the finite element method (FEM) is used to simulate wave propagation through two dimensional (2D) periodic arrays of MWCNTs [25] as well as to explore their performance and potential applications in the area of photonics. Considering anisotropic [4–8] and frequency dependent of dielectric materials, the Lorentz–Drude (LD) oscillator model [26,27] was utilized in a wide frequency range [28]. The triangular lattices of MWCNT arrays, with a lattice constant of 420 nm and nanotube radius of 50 nm as 2D photonic crystals, were modeled and a series of band gaps and transmission bands were observed. Because of strong dependence of MWCNTs and highly sensitivity of PC structures to different polarizations of light, a polarization beam splitter based on MWCNT photonic crystals is proposed in this paper. With the designed polarization beam splitter [29], two orthogonal polarization states of the signal can be divided into absolutely disparate directions. An appropriate choice of parameters makes it possible to guide the TE polarization in a waveguide [30] and transmit the TM polarization in the crystal for a wavelength range covering several important optical windows

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(1310 nm and 1550 nm) for optical communications. Furthermore, the splitter can be used in integrated optical field due to its nanoscale dimension.

2. Study of photonic crystals based on multi-walled carbon nanotubes

A characteristic feature, which distinguishes optical properties of MWCNT arrays from others, is their anisotropic dielectric response that is alike graphite [5–9,31]. Different dielectric functions $\varepsilon_{\|}(\omega)$ and $\varepsilon_{\perp}(\omega)$ depend on electric field being polarized along or perpendicular to *c*-axis, a symmetry axis perpendicular to the base plane of graphite layers. By assuming curvature effects in MWCNTs to be small enough, only $\varepsilon_{\perp}(\omega)$ contribution is considered for electric field polarized parallel to the axis, while for perpendicular polarization both $\varepsilon_{\|}(\omega)$ and $\varepsilon_{\perp}(\omega)$ are needed. It has been shown [31–33] that the dielectric function $\varepsilon(\omega)$ can be fitted with the LD oscillator model [24] and can be expressed as

$$\varepsilon(\omega)=\varepsilon^{(f)}(\omega)+\varepsilon^{(b)}(\omega) \tag{1}$$

where the intra-band effects $\varepsilon^{(f)}(\omega)$ (usually referred to as free-electron effects) is described by the Drude mode and the inter-band effects $\varepsilon^{(b)}(\omega)$ (usually referred to as bound-electron effects) is given by the modified Lorentz model.

$$\varepsilon^{(f)}(\omega)=1-\Omega_p^2/\omega(\omega+i\Gamma_0) \tag{2}$$

$$\varepsilon^{(b)}(\omega)=-\sum_{m=1}^{M}\frac{F_m}{\omega^2-\omega_m^2+\mathrm{i}\omega\Gamma_m} \tag{3}$$

where $\Omega_p^2=f_0\omega_p^2$ is the plasma frequency associated with intra-band transitions with the oscillator strength f_0 and the damping constant Γ_0, m is the number of employed inter-band transition oscillators, Γ_m is the damping constant, and $F_m=f_m\omega_p^2$ characterized by its oscillator strength f_m.

For optical properties of MWCNTs, other research groups have reported that their simulated result can have an excellent fit to experimental data when using $M=7$ for the Drude–Lorentz model [24,33], and thereby, $M=7$ is applied in our calculation with an imaginary part representing loss factor related to dielectric function. The model is based on a function of frequency, allowing practical calculations of optical transmission spectrum of light propagating through the MWCNT-based devices [34]. As shown in Fig. 1(a), the geometry of 2D triangular lattice photonic crystal with MWCNT arrays can be obtained in air by setting dielectric constant as 1. Photonic properties were studied in both TE and TM polarizations, e.g., for TE light polarized with electric field parallel to the tube axis which is vertical into the page. As indicated in Fig. 1(b), the reciprocal lattice primitive cell is the first Brillouin zone, while dark blue shading is its irreducible part, revealing independent photon wave vectors and their highly symmetry for distinct properties of square counterpart.

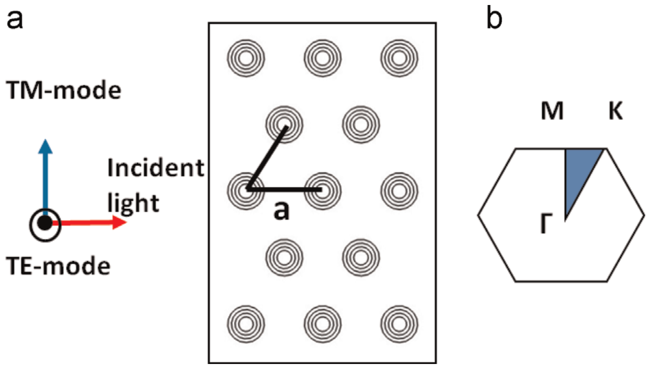

Fig. 1. (a) A schematic of the two dimensional projection of triangular array of MWCNTs with the electric field direction for TE and TM on the left. (b) Reciprocal lattice of the MWCNT structure: the hexagon area is the first Brillouin zone, and dark blue shading is its irreducible part. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

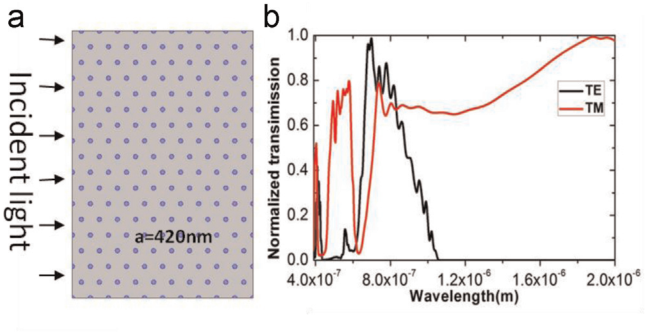

Fig. 2. (a) Model geometry of a 2D triangular array of MWCNTs, with lattice constant of 420 nm and radius of 50 nm. (b) The TE and TM transmission spectrum for the MWCNT-based PC, which illustrates the plasmonic filtering response for TE light while most of light is transmitted in the TM spectrum.

The structure of triangular lattice array of MWCNTs with a lattice constant of 420 nm and nanotube radius of 50 nm is shown in Fig. 2(a). In order to design a polarization beam splitter, the TE (transverse electric) and TM (transverse magnetic) propagation through the periodic nanotube array have been performed separately and the transmission spectrums are presented in Fig. 2(b). It can be found that several band gaps and transmission bands exist in the TE transmission spectrum before 1.05 μm, and after that no more propagation is allowed through the MWCNT arrays. However, a large proportion of the TM light transmits through the PC structure extending from approximately 800 nm, the strong dip is associated with the Bragg condition $\lambda/2\approx a$ [35] which has moved into visible light region because of tube spacing >150 nm [24]. Calculated results obviously show that there is a plasmonic filtering response toward TE polarized light as predicted by the plasmonic theory of metamaterials, while no such cut-off effect is observed in the TM spectrum. This phenomenon results from physical structures of multi-walled carbon nanotubes which allow fast electronic motion within the graphene sheets. Nevertheless, transverse electronic motion on the nanotubes is permitted without significant mutual coupling effect for TM light. So we can realize light confinement in the photonic band-gaps or light propagation in the transmission band for different polarizations by utilizing multi-walled carbon nanotubes. These different transmission characteristics can guide the design of nanotube arrays for nano-photonic applications like waveguides, diffraction gratings, and beam splitters. It has been reported that periodic wire arrays of multi-walled carbon nanotubes with these characteristics can be used as metamaterial high pass filter [36].

3. Design and analysis of polarization beam splitter

It has been found that there is a considerable difference between the TE and TM propagating properties especially above the wavelength of 1 μm, and this appreciable difference can be exploited to design a polarization splitter to separate two orthogonal polarization states. The TE polarized light in the infinitely extending plasmonic band gaps can be guided to any orientation along the introduced line defect in the designed structure, and the TM in the big transmission band can transmit through the structure along the input direction. In order to get the high transmission and low dispersion loss, we should search for and choose

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