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Negative index photonic crystal lenses based on carbon nanotube arrays

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Abstract

We report a novel utilization of periodic arrays of carbon nanotubes in the realization of diffractive photonic crystal lenses. Carbon nanotube arrays with nanoscale dimensions (lattice constant 400 nm and tube radius 50 nm) displayed a negative refractive index in the optical regime where the wavelength is of the order of array spacing. A detailed computational analysis of band gaps and optical transmission through the nanotubes based planar, convex and concave shaped lenses was performed. Due to the negative-index these lenses behaved in an opposite fashion compared to their conventional counter parts. A plano-concave lens was established and numerically tested, displaying ultra-small focal length of 1.5 μm (~2.3 λ) and a near diffraction-limited spot size of 400 nm (~0.61 λ).

Keywords: Multiwalled carbon nanotube arrays; Photonic crystals; Negative index; Negative refraction; Photonic lenses

1. Introduction

Multiwalled carbon nanotubes (MWCNTs) first reported in [1] are very promising materials and have been the focus of enormous research in the past decade. MWCNTs are structurally similar to the concentric arrays of cylindrical tubes made out of single graphite sheets [2]. They are mostly metallic and are able to carry high current densities which paves way towards their extensive utilization in electrical applications, like field emission displays, rectifier electrodes, solar cells and optical antenna arrays [3]. Myriad optical applications of MWCNTs have also been reported exploiting their interesting optical properties [4]. Individual MWCNTs display a frequency dependent dielectric function, which is anisotropic in nature and matches very closely with that of bulk graphite [5,6]. However, the highly dense periodic arrays of MWCNTs may display an artificial dielectric function, with a lower effective plasma frequency in a few hundreds of terahertz, acting as metamaterials [7,8].

It was demonstrated by Pendry et al. [9] that the metallic thin wire arrays, when excited by an electric field parallel to the wires, display a low-density plasma like the electromagnetic response with a reduced plasma wavelength $\lambda_p = a\sqrt{2\pi \ln(a/r)}$, where a is the lattice constant of the 2D wire array, r is the radius of the wires. The arrays display an artificial negative dielectric constant for wavelength regime higher than the plasmon wavelength λ_p, causing reflection. As

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demonstrated in our previous work [7], the CNTs arrays act as plasmonic high pass filters by allowing only the transmission of frequencies modes with wavelengths lower than λ_p. Below the plasmonic wavelength, where the wavelength is of the order of lattice constant a, diffraction dominates and the arrays display effects like photonic band gaps and negative refractive index which are usually affiliated with photonic crystals. The analysis of photonic band gaps and visible diffraction from MWCNT arrays has been previously reported by Kempa et al. [10,11]. However, in this manuscript we report the utilization of two-dimensional (2D) periodic arrays of MWCNTs for achieving negative index photonic crystal lenses, with ultra small focal lengths and near diffraction-limit spot sizes. To the best of our knowledge we for the first time report the detailed investigation of wave propagation through the CNT arrays and negative index lensing effects. The arrays with nanoscale dimensions (lattice constants of 400 nm) displayed diffraction based negative index lensing effects in the optical regime. Plasmonic filtering effects were observed for higher wavelength.

2. Negative refraction in CNT array based photonic crystals

Negative index lenses can be constructed by using negative dielectric materials like thin metallic slabs [12] which acts as a metamaterials or by using photonic crystals which present a periodicity in their dielectric constant [13]. In the case of photonic crystals, the size and periodicity of the scattering elements (nanotubes) are on the order of wavelength of incident light, causing Bragg diffraction. The diffractive phenomena in photonic crystals can lead to the excitation of waves for which phase and group velocities are reversed in the same manner as in negative index metamaterials. Thus, under the right conditions, negative refraction can be observed in photonic crystals [14].

While following the same principle we report computational analysis of negative diffraction effects in periodic carbon nanotube arrays. We first performed band structure calculations by using plane wave expansion (PWE) method [15], in order to find out the potential frequency ranges where the CNT arrays exhibit a negative refractive index. The analysis was performed for transverse electric (TE) mode of light polarized parallel to the CNTs. Due to the computational constraints a dispersionless model was used without the absorption characteristics of the nanotubes. Only the real part Calculated band structure results for an array with lattice constants of 400 nm and tube radius

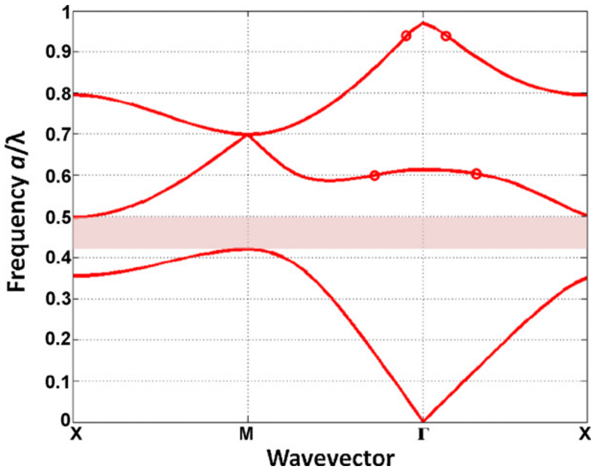

Fig. 1. Calculated TE band structure for a square lattice carbon nanotube array with a = 400 nm and r = 50 nm.

of 50 nm are presented in Fig. 1. A negative band slope was observed at two frequency ranges around 420 nm ($a/\lambda \approx 0.95$) in band 3 and 670 nm ($a/\lambda \approx 0.6$) in band 2. It has been reported that photonic crystal exhibiting negative band slope demonstrate a backwards electromagnetic wave propagation [16,17]. Therefore, an effective negative refractive index can be defined at these frequencies, meaning negative refraction could occur in through the carbon nanotube array.

To further study the negative refraction effects, we performed a finite element method (FEM) analysis of optical transmission through the carbon nanotube array. For the sake of simplicity we considered a 2D geometry of square lattice CNT array (Fig. 2) and the electromagnetic field was assumed to be invariant along the axis of the nanotubes (z axis). The dielectric constant of the multiwalled carbon nanotubes was obtained using the Drude–Lorentz model reported in [4] and was incorporated into the model as a frequency dependent function. The calculations were performed for the light polarized parallel to the CNTs (TE) and ranging from 400 nm to 1000 nm. First we simulated the propagation of an oblique incident plane wave (with a 30° angle of incidence) across a CNT array, as shown in Fig. 2(a). Negative refraction was observed across the array near the wavelengths of 470 nm and 675 nm. Transmission spectrum calculation across the CNT array also revealed the highest transmission intensity near these wavelength regimes (Fig. 2(b)).

The simulation was also repeated for a point source of light, as shown in Fig. 2(c). The CNT array exhibited a negative effective index and reconstructed the image of the point source on the opposite side. The array acts as a negative index planer lens [16]. The transmission spectrum was calculated near the image of the point