Optik 159 (2018) 123–132

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Scattering of electromagnetic waves by a graphene-coated thin cylinder of left-handed metamaterial

Hamid Pashaeiadl[a], Mahin Naserpour[a,b], Carlos J. Zapata-Rodríguez[a,*]

[a] Department of Optics and Optometry and Vision Science, University of Valencia, Dr. Moliner 50, Burjassot 46100, Spain
[b] Physics Department, College of Sciences, Shiraz University, Shiraz 71946-84795, Iran

ARTICLE INFO

Article history:
Received 27 July 2017
Received in revised form
25 December 2017
Accepted 18 January 2018

Keywords:
Scattering
Graphene
Left-handed metamaterials

ABSTRACT

In this paper, we explored the scattering behavior of thin cylinders made of a left-handed material (LHM) and coated by a monoatomic graphene layer. A spectral tunability of the resonance peaks is evidenced by altering the chemical potential of the graphene coating, a fact that occurs at any state of polarization of the incident plane wave in opposition to the case of scatterers of dielectric core. On the contrary, no invisibility condition can be satisfied for dielectric environments. A singular performance is also found for cylinders with permittivity and permeability near zero. Practical implementations of our results can be carried out in sensing and wave manipulation driven by metamaterials.

1. Introduction

Fabrication of metal-dielectric structures exhibiting exotic electromagnetic properties ranging from microwaves to visible wavelengths has recently been enabled by current micro- and nano-technology [1–4]. For terahertz frequencies, homogeneous and isotropic artificial materials have effectively been manufactured showing negative permittivity and permeability simultaneously [5–7]. Such terahertz metamaterials were proposed for a great variety of applications including polarizers [8], subwavelength imaging [9], far-field focusing [10,11], and cloaking [12], to mention a few.

The scattering properties of bodies made of metamaterials including negative-index media have been studied considering different shapes like cylinders [13,14], tubes [15,16], spheres [17,18], and also as coatings over dielectrics and metals [19–22]. Tunability of such properties are subject to modification of its internal geometrical configuration, which on the other hand is not always easily accessible.

The advent of graphene technology involving for instance the creation of widely tunable devices in the THz regime by simply incorporating atomically-thin layers is currently in fast development [23]. Thus, particles coated by monoatomic films have been proposed for electrochemical sensing, invisible cloaking [24], and improved biomedical applications based on the photothermal effect [25]. Particularly interesting results a recently published paper concerning a graphene-coated sphere in the case that the sphere is of negative refractive index [26]. Here we investigate the resonant behavior of subwavelength LHM cylinders coated by graphene in the terahertz regime, which exhibit an anisotropic response on the polarization of the incident wave field.

Finding the way to transfer a graphene film onto an extrinsic substrate is essential. Apparently, direct deposition of the graphene coating around the surface of a LHM cylinder to form a graphene-coated LHM cylindrical scatterer can be accom-

* Corresponding author.
E-mail address: carlos.zapata@uv.es (C.J. Zapata-Rodríguez).

https://doi.org/10.1016/j.ijleo.2018.01.056
0030-4026/

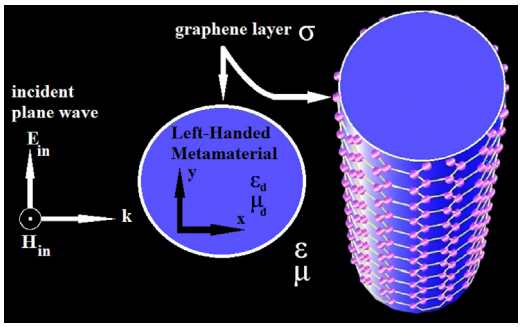

Fig. 1. Illustration of the scattering particle coated by an atomically-thin graphene layer and illuminated by a TE^z-polarized plane wave.

plished with current nano-fabrication technology. For instance, a chemical vapor deposition method using centimetre-scale flexible copper substrates and wet-chemical doping of predominantly monolayer graphene films enabled the production of transparent electrodes to be used in solar cells, touch sensors and flat panel displays [27,28]. On a smaller scale, large-area graphene films transferred onto microfiber substrates with diameters of ∼10 μm were used for sensor devices and signal processing [29–31]. Graphene encapsulation shown interesting effects on the properties of the interior phase can be miniaturized in the nanometer scale. For instance, graphene nanochannels were synthesized as templates which interior can be filled with fluids and solid materials like metals [32,33]. The experimental precedents shown above demonstrate that manufacturing high-quality graphene cloaks on cylindrical LHM substrates is effectively available.

Our hybrid LHM-graphene scatterer offers the prospect of manipulating the surface conductivity of the monoatomic coating through electrical/magnetic bias or chemical doping, via controlling its Fermi level, thus providing a convenient platform for applications demanding reconfiguration. In this respect, a modulated chemical doping of individual single-walled carbon nanotubes was reported, including gate-tunable nanotube p-n junctions [34]. Tunability achieved by means of chemical doping was also demonstrated in plasmonic structures consisting of graphene/insulator stacks arranged in disk arrays [35]. Alternatively, electrostatic doping of graphene enables to inject charge carriers on the conducting sheet thus modifying the characteristics of the plasmon modes of the optical resonator [36,37]. Though not covered by this study, a concentric graphene-coated cylinder might take profit of self-biasing graphene layers [38]. We also disregard magnetically biased graphene sheets since it will lead to coupling of TE and TM modes caused by the tensorial nature of graphene conductivity [39]. By means of numerical simulations we will show how alterations of the chemical potential in graphene by simply applying a gate voltage can serve to dynamically control the resonant peaks of the resultant scattering cross section of the Mie scatterers.

2. Theoretical analysis

Let us consider a cylindrical dielectric nanowire of radius R and relative permittivity ϵ_d and magnetic permeability μ_d covered by an atomically thin graphene monolayer, and oriented along the z axis, as illustrated in Fig. 1. The nanowire is assumed to be placed in an environment medium of the relative permittivity ϵ and magnetic permeability μ; for simplicity, here we assume that the environment medium is lossless. The wave vector of the incident radiation is directed along the x axis, and in this case two fundamental polarization configurations can be studied: (1) the electric field vector $\vec{E_{in}}$ lying in the xy plane (TE^z-polarized plane wave or $E_z = 0$ modes), and (2) the magnetic field $\vec{H_{in}}$ lying in the xy plane (TM^z-polarized plane wave or $H_z = 0$ modes). The graphene conductivity was described according to the local random phase approximation of the Kubo formula [40] which can be expressed as $\sigma = \sigma_{intra} + \sigma_{inter}$, where the intraband contribution can be written as

$$\sigma_{intra} = \frac{2ie^2 k_B T}{\pi\hbar^2(\omega + i\Gamma)} \ln\left[2\cosh\left(\frac{\mu_{ch}}{2k_B T}\right)\right], \tag{1}$$

and the interband contribution is expressed as

$$\begin{aligned}\sigma_{inter} &= \frac{e^2}{4\hbar}\left[\frac{1}{2} + \frac{1}{\pi}\arctan\left(\frac{\hbar\omega - 2\mu_{ch}}{2k_B T}\right)\right] \\ &\quad - \frac{e^2}{4\hbar}\left[\frac{i}{2\pi}\ln\frac{(\hbar\omega + 2\mu_{ch})^2}{(\hbar\omega - 2\mu_{ch})^2 + (2k_B T)^2}\right].\end{aligned} \tag{2}$$

In this expression, $-e$ is the charge of an electron, $\hbar$ is the reduced Plank's constant, k_B is Boltzmann's constant, T is the temperature, Γ is the charge carriers scattering rate, μ_{ch} is the chemical potential and $\hbar\omega$ is the photon energy. Also, an $\exp(-i\omega t)$ time-dependence is implicit throughout the paper, where ω is the angular frequency, t the time coordinate, and $i = \sqrt{-1}$.