Carbon 100 (2016) 74–80

Contents lists available at ScienceDirect

Carbon

journal homepage: www.elsevier.com/locate/carbon

Metamaterials in multilayer graphene photonics: Control of negative refraction

Haixia Da [a, b, *], Xiaohong Yan [a, b, c, **]

[a] Nanjing University of Posts and Telecommunications, College of Electronic Science and Engineering, Nanjing, Jiangsu, 210046, China
[b] Key Laboratory of Radio Frequency and Micro-Nano Electronics of Jiangsu Province, Nanjing, 210023, China
[c] College of Science, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu, 210016, China

ARTICLE INFO

Article history:
Received 10 May 2015
Received in revised form
28 December 2015
Accepted 30 December 2015
Available online 4 January 2016

ABSTRACT

Negative refraction medium can in principle be realized using artificial composites composed of semiconductor/metallic inclusions, which experience negative refraction over certain frequency region due to structural resonant. It would be desirable if we could extend negative refraction to alternative natural semimetal candidates. Here, we show that by employing multilayer-graphene and cubic boron nitride slab, the composite may support negative group refractive angle over certain frequencies due to its anisotropic characteristics. Poynting vector profile numerically demonstrates that transverse magnetic wave propagates with observable negative shift as if they had negative refractive index.
© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

In contrast to the well-known conventional refraction theory, negative refraction (NR) is a new concept which refers to the fact that the refraction and incident rays stay at the same side when the beam encounters the interface [1]. The experimental realization of this kind of materials in artificial structures has sparked considerable interest owing their fundamental new physics and potential applications in optical devices, such as subwavelength images, superlens and clocking [2–8]. Existing proposals for realizing NR materials mainly rely on the conventional resonant-mediated mechanism [9–13]. By well designing subwavelength metamaterials, it is possible to achieve negative permittivity and permeability simultaneously at a certain frequency region owing to the possible resonances involved. Such a mechanism gives rise to NR properties within relatively complex geometrical structures, resulting in some difficulties in experimental fabrications. Apart from the above resonant mechanism, another scenario is proposed to create NR effect. It have been experimentally demonstrated that both two-dimensional metal wire and one-dimensional semiconductor multilayer structure support NR effect due to their intrinsic strong anisotropy [14,15]. Such a scheme is based on multilayer structure and thus this will be relatively easy in fabrication.

Producing a controlled NR effect is a topic of central importance. The availability of an adjustable NR effect opens up the possibility of a much wider range of applications. The altering optical properties of metamaterials can be achieved by adding other components or engineering the geometrical configuration. For example, both experimental and theoretical investigations have revealed that tunable NR effect can be induced by photodoping a piece of low-doped semi-conductor positioned within the gap of the resonator, applying drops of silicon nanospheres to the split ring array, or photoexcitation of free carriers in the substrate [16–21]. From experimental perspective, however, the above schemes impose certain difficulty in fabrication. Therefore, the materials, which have intrinsic tunable optical properties, may serve as a platform for controllable optical devices by external means other than modifying geometrical configurations. The tunable functionality of the composite essentially relies on the sensitivity of permittivity/permeability on the external stimulus, enabling the controlled NR effect. Superconductor or ferromagnetic materials have been put forward to be the candidates, realizing tunable NR effect with the advantages of easiness of controllability, such as temperature or magnetic field [22–24]. But these approaches suffer from the transition from the superconductor/ferromagnetic state to normal conductor/paramagnetic state.

Graphene, a two-dimensional monolayer of carbon atoms

* Corresponding author. Nanjing University of Posts and Telecommunications, College of Electronic Science and Engineering, Nanjing, Jiangsu, 210046, China.
** Corresponding author. Nanjing University of Posts and Telecommunications, College of Electronic Science and Engineering, Nanjing, Jiangsu, 210046, China.
E-mail addresses: eledah@njupt.edu.cn (H. Da), yanxh@njupt.edu.cn (X. Yan).

http://dx.doi.org/10.1016/j.carbon.2015.12.097
0008-6223/© 2016 Elsevier Ltd. All rights reserved.

arranged in a hexagonal lattice, has attracted great interest owing to its unusual electronic band structure [25]. The carriers of graphene are characterized by massless Dirac fermions, whose behaviors are governed by Dirac equation. The linear dispersion leads to its unique relativistic physical properties, such as integer and fractional quantum Hall effect, absence of backscattering and Klein tunneling [26–28]. Besides, graphene also exhibits fantastic optical properties owing to its unique optical conductivity. In this regard, graphene could be used to manipulate optical information because it is found to be extremely sensitive to external stimulus due to its ultrathin thickness. The AC conductivity of graphene has a strong dependence on chemical potential as well as magnetic field. Such a unique property of graphene makes it a promising candidate for tunable optical devices, including tunable plasmonics, gate-controlled active graphene metamaterials, transformation optics, clocking, broadband polarizer, lens, giant Faraday rotation and optically transparent conductor [25–37].

It has been proposed that graphene with a well-designed optical conductivity distribution supports control of beam propagation, collimation, and focusing [38]. Therefore, one can imagine the possibility of tunable NR effect using carbon-based derivatives. In fact, the NR effect in thin graphite films has been advanced based on degenerate four-wave mixing [39]. In this approach, nonlinearity is the basic requirement to realize negative refractive angle. Graphite flakes with few graphene layers are used to lower the challenge in setting up the phase conjugation. This phenomenon reveals another unique optical property of graphite. However, the counter-propagating beams with strong electric fields are necessary due to the required nonlinearity, imposing the difficulty in experiment.

We know that the thickness is an important issue in designing the optical devices. However, the fixed thickness of graphene limits the direct applicability of the conventional optical effects to some extents. Increasing the layer number of graphene provides a possibility for overcoming this. In contrast to monolayer graphene, multilayer graphene has a more complex geometrical configuration because of different stacking sequences, which gets more rich physics and has its own contributions to optical fields due to the interlayer couplings. For example, gate tunable infrared phonon anomalies and an unusual giant Kerr effect have been reported in bilayer graphene due to the extra interlayer couplings between two layers [40,41]. The exploration of optical properties in few-layer graphene is still in early stage, which deserves more attention. It has been experimentally reported the lifetime of hot carriers in few-layer graphene appears to be longer than those in epitaxial graphene and graphite, indicating it is an important optoelectric material in high speed optoelectronics such as absorbers and modulators [42]. Besides, the optical transmittance of multilayer graphene can be modulated by means of an electrical signal in the simple configuration of coplanar electrodes [43]. Therefore, it offers new opportunities to explore an electrically controlled optical effect in terahertz metamaterials infiltrated with multilayer graphene. However, few reports concerning the tunable optical effects based on multilayer graphene have been presented in the literature.

Here we theoretically demonstrate a new mechanism for the chemical-potential manipulated NR effect. It can be realized by stacking multilayer graphene with Bernal sequence together where the spaces between the neighbor multilayer graphene are filled with dielectric materials, i.e., cubic boron nitride (BN). Owing to the Drude-like dynamics of multilayer graphene at low frequency regime, it provides the negative permittivity over a certain frequency. The existence of the multilayer graphene and BN slab lead to an effective anisotropic characteristic of the composite, whose anisotropic properties enable the observation of NR phenomenon. The spatial-distributed field intensity and power distribution figures are a manifestation of anisotropic feature, where the NR happens at transverse magnetic polarization (TM) but not for transverse electronic polarization (TE). In addition, similar to the single layer graphene, multilayer graphene is also sensitive to the gate voltage [44], thus the gate bias-sensitive NR is also investigated. Our results suggest that tunable NR effects are observed in multilayer graphene instead of single layer graphene. Importantly, this function can be extended to multilayer graphene with more layers and random orientation, making it more feasible for optical measurement in experiment. Thus, tunable NR effect can be realized by designing multilayer graphene with different layer numbers and stacking sequence other than nonlinearity, avoiding the need of strong incident pumps.

2. Methodology

A periodic structure is proposed which consists of alternating multilayer Bernal stacking graphene and dielectric materials as schematic figure shown in Fig. 1. The multilayer graphene lies in the x-y plane, which is separated by a normal dielectric BN slab. Multilayer Bernal stacking graphene is used as a candidate due to the fact that the same configuration with single layer graphene doesn't support NR properties (See Supplement file for details). BN is chosen as the spacer material due to the experimentally demonstrated good sample quality when graphene sits on it. z is propagating direction and a THz plane wave impinges upon the structure with an angle θ_i. A TM polarized light is a wave with the magnetic field perpendicular to the plane of incidence (xz), while TE polarized light is the wave with the electric field perpendicular to the plane of incidence. The thicknesses of multilayer graphene and BN slab are d_1 and d_2, respectively. m is the repetition number of the structure.

The phase (θ_p) and group (θ_s) refractive angles are given by Ref. [45].

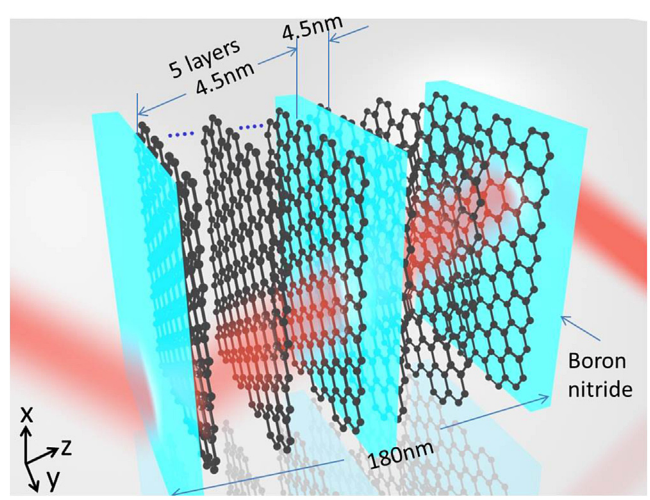

Fig. 1. Schematic of the negative refraction effect in multilayer graphene/cubic BN metamaterials. The sheets with black balls and lines show the schematic structure of multilayer graphene. The large space scale is taken for better visualization of multilayer graphene's geometry. Cubic BN is the spacer, which stacks with multilayer graphene alternatively. The thicknesses of multilayer graphene, cubic BN and total thickness of the stack are indicated in figures. An external gate voltage can be used to control the chemical potential of multilayer graphene. (A color version of this figure can be viewed online.)

Download English Version:

https://daneshyari.com/en/article/7850082

Download Persian Version:

https://daneshyari.com/article/7850082

Daneshyari.com