Multiphysics Modeling of a Triple-Scale Graphene Sheet - Magnetic Nanowire - FSS Gyrotropic Metasurface

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Abstract

A multi-scale gyrotropic metasurface composed of three stacked layers – a graphene sheet, a magnetic nanowire membrane and a frequency selective surface (FSS), acting as a transparent Faraday rotator, is analyzed. The analysis consists in a self-consistent multi-physics modeling, involving magneto-statics, electromagnetics, transport and diffusion. The periodic coupled Maxwell-Boltzmann equations are solved in the Fourier domain.

1. Introduction

Graphene is a one-atom thick, and therefore electromagnetically 2D, structure consisting of carbon atoms organized according to a honeycomb "lattice". The massless Dirac fermions in graphene cause novel phenomena such as the half integer quantum Hall effect [1–3], giant Faraday rotation [4], electrically tunable gyrotropy [5] and exotic non-reciprocal plasmonic modes [6–14]. Magnetically biased graphene has shown potential for non-reciprocal and gyrotropic electromagnetic devices [4, 5]. Moreover, with the application of an electrical bias the graphene based non-reciprocal devices acquire the advantage of electrical tunability [11]. Some applications, such as Faraday rotation, however, demand electromagnetic transparency as well. Although a magnet could maintain the intrinsic transparency of graphene, it is bulky and expensive and inappropriate for practical devices. We recently proposed a stack of graphene, a ferromagnetic nanowires (FMNW) layer and a frequency selective surface (FSS) as a candidate for transparent tunable gyrotropic graphene-based Faraday rotators [15]. This gyrotropic metasurface combines different physics including magneto-statics, electromagnetics, transport and diffusion, demanding a multi-physics analysis. This paper presents a multi-physics approach for the analysis of this multi-scale structure.

2. Triple-scale gyrotropic metasurface

The proposed graphene – FMNW membrane- FSS metamaterial structure is shown in Fig. 1. The FMNW membrane provides a reasonable magnetic bias for Faraday rotation. This layer is composed of ferromagnetic material nanowires arranged in a hexagonal lattice with periodicity in the order of 100 nm. It generates a periodic magnetic field peaking to about 0.5 T beneath the graphene layer. This layer has a thickness of a few microns and is electromagnetically transparent at microwave and terahertz frequencies [16, 17]. Electric tunability is provided by the application of a voltage between graphene and the FSS layer, where the FSS acts as a transparent ground by proper design [18, 19]. The entire structure is transparent and can act as a tunable Faraday rotator metasurface.

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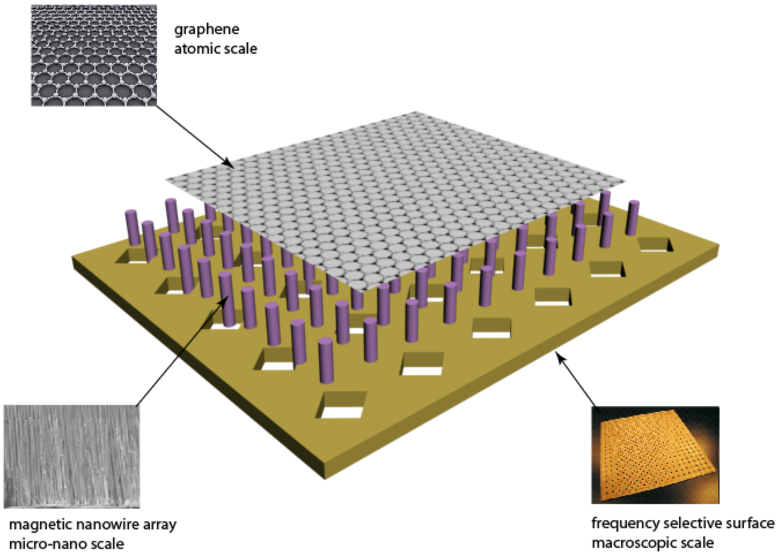

Figure 1: Transparent gyrotropic metasurface. Stack of graphene sheet, ferromagnetic nanowire membrane and frequency selective surface (FSS).

2. Multiphysics analysis

Each layer in the proposed metamaterial exhibits completely different characteristic length scales and distinct physical properties. The graphene layer is composed of carbon atoms arranged in a honeycomb structure with a interatomic distance of 1.42 A, the FMNW membrane layer has a length scale of the order of 100 nm [16, 17], and the FSS has macroscopic length scales in the order of 1 mm to several centimeters, depending on the frequency of operation. Moreover, the non-uniformity of the biasing magnetic field makes the analysis challenging. This periodic non-uniformity induces a periodic non-uniform current density on the graphene sheet. Accurate treatment of the problem requires a self-consistent analysis considering the coupling of several physics, including magneto-statics, electromagnetics, carrier transport and diffusion. The Boltzmann transport equation is used to describe the carrier transport in graphene. The static magnetic field generated by the FMNW and the time harmonic incident, reflected and transmitted electromagnetic fields shown in Fig. 2 couple to the Boltzmann equation via the Lorentz force:

$$\frac{\partial f(t,\mathbf{r},\mathbf{p})}{\partial t} + \mathbf{v}(\mathbf{p})\cdot\nabla_{\mathbf{r}} f(t,\mathbf{r},\mathbf{p}) + \mathbf{F}(t,\mathbf{r})\cdot\nabla_{\mathbf{p}} f(t,\mathbf{r},\mathbf{p}) = \frac{f_0(\mathbf{p}) - f(t,\mathbf{r},\mathbf{p})}{\tau}, \tag{1}$$

$$\mathbf{F}(t) = q\mathbf{E}_{ac}(t,\mathbf{r}) + q\mathbf{v}(\mathbf{p})\times\mathbf{B}(t,\mathbf{r}), \tag{2}$$

$$\mathbf{B}(t,\mathbf{r}) = \mathbf{B}_{ac}(t,\mathbf{r}) + \mathbf{B}_0(\mathbf{r}), \tag{3}$$

where $f(t,\mathbf{r},\mathbf{p})$ is the career distribution function, $\mathbf{E}_{ac}(t,\mathbf{r})$ and $\mathbf{B}_{ac}(t,\mathbf{r})$ represent the total harmonic electromagnetic fields, and $\mathbf{B}_0(\mathbf{r})$ represents the periodic static magnetic field. The Boltzmann transport equation (1) involves two periodicities with different length scales, the periodic momentum $\mathbf{p}$ with atomic scale periodicity (through the Brillouin zone of graphene), and the periodic space $\mathbf{r}$ with micro-nano scale periodicity (through the periodic static magnetic field). The momentum periodicity is handled by taking the first moment of the Boltzmann transport equation, which transforms the microscopic momentum variable into macroscopic quantities such as the electric current density. The resulting one-fold periodic problem is then solved in the Fourier domain.

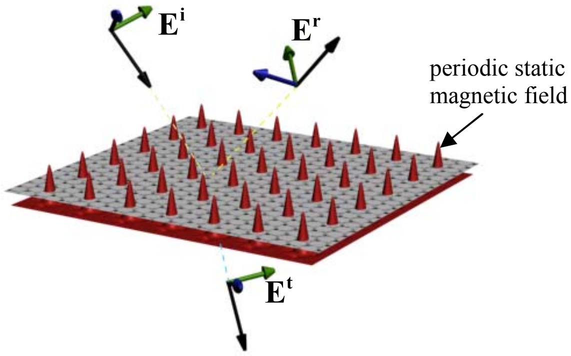

Figure 2 : Graphene sheet in a periodic static magnetic field.

4. Conclusions

A self-consistent multi-physics approach is developed to accurately simulate a multi-scale transparent gyrotropic metasurface. The coupled Maxwell-Boltzmann equations properly model the interacting magneto-statics, electromagnetics, transport and diffusion phenomena.

5. References

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