Graphene Magnetoplasmons in Periodic Magnetic Fields

Nima Chamanara[1] and Christophe Caloz[2]

[1] Poly-Grames Research Center, École Polytechnique de Montréal, Montréal, Québec H3T 1J4, Canada.
e-mail: nima.chamanara@polymtl.ca

[2] Poly-Grames Research Center, École Polytechnique de Montréal, Montréal, Québec H3T 1J4, Canada.
e-mail: christophe.caloz@polymtl.ca

Abstract

Magnetoplasmons in a graphene sheet immersed in a periodic magnetic field produced by a ferromagnetic nanowire membrane are analyzed. The periodic magnetic field modifies the classical cyclotron radii and generates a periodic non-uniform carrier density. Depending on the strength of the magnetic field and the corresponding cyclotron radii, different regimes requiring different treatments are identified and analyzed.

1.Introduction

Graphene, a zero thickness carbon material arranged according to a honeycomb structure, has recently revealed unprecedented fundamental phenomena such as giant Faraday rotation [1] and half integer quantum Hall effect [2–4], and has spurred significant research interest since its first production in 2004 [2–4]. As a 2D electron gas, under a magnetic bias the carriers in graphene follow elliptical cyclotron orbits, when excited by an incident electric field. The cyclotron motion results in an anti-symmetrical 2D conductivity tensor, and is responsible for gyrotropic properties of graphene, such as Faraday rotation. Faraday rotation is a transmission effect, and demands a structure which is transparent to electromagnetic waves. Although magnets could be used for this purpose, for practical applications they are bulky, heavy and expensive. We recently proposed a multi-scale transparent gyrotropic metamaterial, composed of a stack of graphene, a ferromagnetic nanowire membrane and a frequency selective surface, as a candidate for practical graphene based Faraday rotators [5]. In this metamaterial, graphene is immersed in a periodic magnetic field. This structure is analyzed using a multi-physics model combining magneto-statics, electromagnetics, carrier transport and diffusion [5]. In oblique incidence the propagating surface mode of the graphene sheet in a periodic magnetic field, will enter the picture as well, and should be taken into account. In this paper we investigate these magnetoplasmonic modes for an infinite graphene sheet in a periodic magnetic field.

2. Magnetoplasmons in periodic magnetic fields

At terahertz and optical frequencies where the imaginary part of the conductivity of graphene becomes significant compared to its real part, graphene supports surface plasmons, and in the presence of a magnetic bias, magnetoplasmons. A graphene strip supports an infinite number of bulk magnetoplasmon modes with transverse resonances and two edge modes. These edge modes show interesting non-reciprocal properties, with applications in non-reciprocal graphene-based plasmonic devices such as non-reciprocal phase shifters, non-reciprocal couplers and isolators [6–8]. With the application of an electric bias these non-reciprocal devices get endowed with the additional flexibility of electrical tenability [8, 9]. The non-reciprocity in the presence of a magnetic bias appears through an anti-symmetric conductivity tensor resulted from the cyclotron motion of carriers in magnetically biased graphene.

978-1-4673-5225-3/14/$31.00 ©2014 IEEE

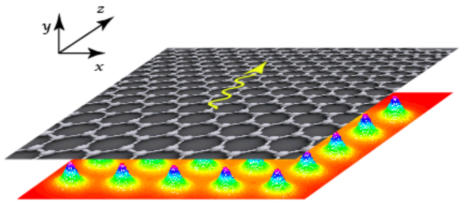

Figure 1: Graphene magnetoplasmons in a periodic magnetic field.

For graphene magnetoplasmons in a periodic magnetic field, shown in Fig. 1, the classical cyclotron orbits get modified. The periodic magnetic field generates a periodic non-uniform carrier density. Depending on the strength of the magnetic field and the corresponding cyclotron radii the problem will enter different regimes requiring different strategies [5]. For cyclotron radii much larger than the FMNW periodicity [11,12] shown in Fig. 2(a), the carriers sense an average magnetic field along their path, and a uniform averaged magnetic field would be a good approximation. For cyclotron radii much smaller than the FMNW periodicity shown in Fig. 2(b), the carriers sense a local magnetic field. In this case graphene can be modeled as a local tensorial periodic conductivity sheet. For cyclotron radii comparable to the magnetic field periodicity shown in Fig. 2(c), the problem enters a non-local regime where the averaging and local techniques are not accurate. In this case, we are dealing with a non-local multiscale multyphysics problem involving magneto-statics, carrier transport, electromagnetics and diffusion. These regimes are investigated in details through analysis appropriate for each scenario.

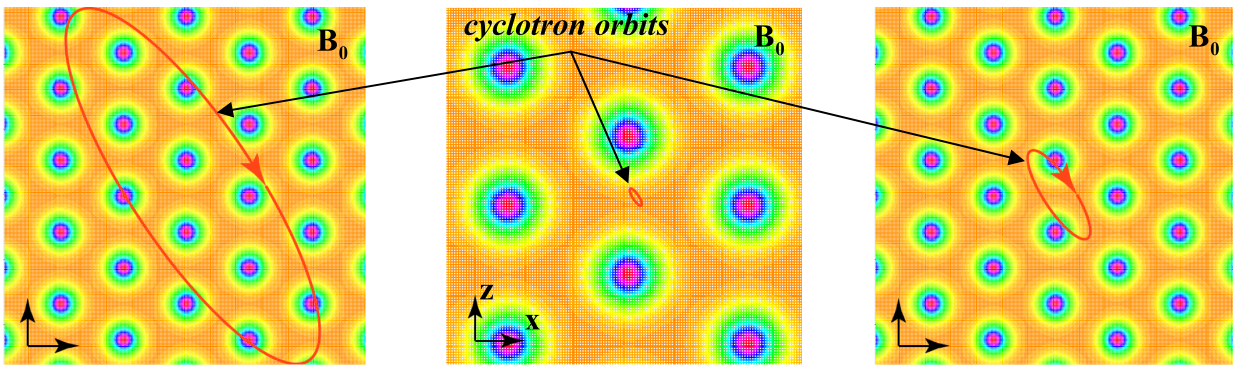

Figure 2: Cyclotron radii for different regimes. (a) Average, (b) local conductivity and (c) non-local regime.

3. Conclusions

Magnetoplasmons in a graphene sheet immersed in a periodic magnetic field generated by a ferromagnetic nanowire membrane, are analyzed. Depending on the strength of the magnetic field and the corresponding cyclotron radii, average, local conductivity and non-local regimes requiring different treatments are identified and analyzed accordingly.

4. References

1. D. L. Sounas and C. Caloz, "Electromagnetic nonreciprocity and gyrotropy of graphene," *Appl. Phys. Lett.*, vol. 98, no. 2, pp. 021911–021911, 2011.

2. K. Novoselov, A. K. Geim, S. Morozov, D. Jiang, M. K. I. Grigorieva, S. Dubonos, and A. Firsov, "Two-dimensional gas of massless Dirac fermions in graphene," *Nature*, vol. 438, no. 7065, pp. 197–200, 2005.

3. A. K. Geim and K. S. Novoselov, "The rise of graphene," *Nat. Materials*, vol. 6, no. 3, pp. 183–191, 2007.

4. A. C. Neto, F. Guinea, N. Peres, K. S. Novoselov, and A. K. Geim, "The electronic properties of graphene," *Rev. Modern Phys.*, vol. 81, no. 1, p. 109, 2009.

5. N. Chamanara and C. Caloz, "Multiscale and Multiphysics Graphene Sheet – Magnetic Nanowire Gyrotropic Metamaterial," in *AP-S Int. Antennas Propagat. (APS),* 2014, *to be published*.

6. D. L. Sounas and C. Caloz, "Edge surface modes in magnetically biased chemically doped graphene strips," *Appl. Phys. Lett*., vol. 99, no. 23, pp. 231902–231902, 2011.

7. N. Chamanara, D. L. Sounas, and C. Caloz, "Non-reciprocal magnetoplasmon graphene coupler," *Opt. express*., vol. 21, no. 9, pp. 11248–11256, 2013.

8. N. Chamanara, D. L. Sounas, and C. Caloz, "Graphene magnetoplasmons: Principles and applications," in *Antennas and Propagation (EuCAP), 2013 7th European Conference on*, pp. 496–497, IEEE, 2013.

9. N. Chamanara, D. L. Sounas, and C. Caloz, "Non-reciprocity with graphene magnetoplasmons and application to plasmonic isolators," in *Electromagnetic Theory (EMTS), Proceedings of 2013 URSI International Symposium on*, pp. 266–268, IEEE, 2013.

10. N. Chamanara, D. L. Sounas, T. Szkopek, and C. Caloz, "Terahertz magnetoplasmon energy concentration and splitting in graphene pn junctions," *Opt. express*., vol. 21, no. 21, pp. 25356–25363, 2013.

11. L.-P. Carignan, V. Boucher, T. Kodera, C. Caloz, A. Yelon, and D. Ménard, "Double ferromagnetic resonance in nanowire arrays," *Appl. Phys. Lett*., vol. 95, no. 6, pp. 062504–062504, 2009.

12. L.-P. Carignan, A. Yelon, D. Menard, and C. Caloz, "Ferromagnetic nanowire metamaterials: Theory and applications," *Microw. Theory Tech. IEEE Transactions on*., vol. 59, no. 10, pp. 2568–2586, 2011.