Graphene plasmons for couplers and hyperbolic metamaterials

Ilya V. Shadrivov,[1*] Daria A. Smirnova,[1] Ivan V. Iorsh,[2,3] Andrey V. Gorbach,[4] Ivan S. Mukhin,[2,5] Pavel A. Belov,[2] and Yuri S. Kivshar

[1]Nonlinear Physics Centre, Australian National University, Canberra ACT 0200, Australia
[2]National Research University of Information Technologies, Mechanics and Optics (ITMO), St. Petersburg 197101, Russia
[3]Department of Physics, Durham University, DH1 3LE Durham, United Kingdom
[4]Centre for Photonics and Photonic Materials, Department of Physics, University of Bath, Bath BA2 7AY, UK
[5]St. Petersburg Academic University, Nanotechnology Research and Education Center, St. Petersburg 194021, Russia
*corresponding author, E-mail: ivs124@physics.anu.edu.au

Abstract

We study propagation of electromagnetic waves in two closely spaced graphene layers and demonstrate that this double-layer graphene waveguide can operate as an optical coupler for both continuous plasmons and spatial plasmon-solitons. We further study multilayer graphene structures and show that they are good candidates for realizing hyperbolic metamaterials for THz frequencies. We show theoretically that tuning from elliptic to hyperbolic dispersion in such structure can be achieved with an external gate voltage.

1. Introduction

Graphene is a two-dimensional crystal of carbon atoms, which exhibits remarkable characteristics. Recently, its unique optical properties have generated significant interest in the research community [1]. An optical response of graphene is characterized by a surface conductivity which is related to its chemical potential and Fermi energy. At certain frequencies, graphene behaves as a metal, and its coupling to electromagnetic waves may support different types of surface plasmon polaritons, which are described theoretically and have been already observed in experiments [2]. These features make graphene a promising material for plasmonics, paving a way towards the development of optical metadevices.

Nonlinear optical properties of graphene structures have attracted attention only recently. Large values of nonlinear optical susceptibilities have been predicted theoretically, and recently they were verified experimentally for the third order nonlinear response. This finding opens a way for the exploration of strong nonlinear photonic effects in graphene structures, including nonlinear self-action of surface plasmons in graphene and the generation of subwavelength spatial solitons [3].

2. Graphene coupler

We study analytically and numerically the nonlinear propagation of light in two coupled layers of graphene (see Fig. 1), and demonstrate that this simple double-layer structure can operate as an efficient optical coupler for both continuous plasmon polaritons and for subwavelength spatial solitons. We demonstrate the nonlinearity-induced symmetry breaking in this graphene coupler and discuss a physical mechanism for optical beam control and manipulation.

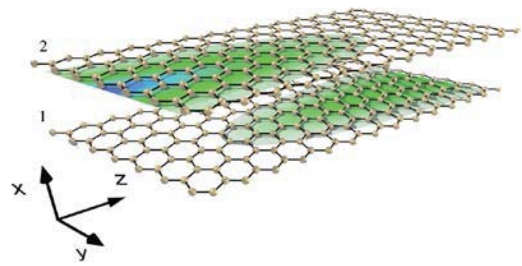

FIG. 1 Schematic of a nonlinear graphene coupler composed of two layers of graphene. The color pattern demonstrates how a plasmon beam excited in the top layer tunnels to the bottom layer (numerical results not to scale).

We compare the switching characteristics of the nonlinear graphene coupler for the continuous plasmons and for the beams of a finite extent including the soliton switching and discuss the case when two in-phase beams of an identical shape are launched into both layers, being shifted initially by a half of their width with respect to each other. We show that two regimes of the coupler operation can be clearly distinguished and the beam may be effectively routed between the graphene layers by changing its input power [4].

3. Hyperbolic medium

Next, we suggest a novel class of hyperbolic metamaterials where individual graphene sheets are separated by host dielectric layers [5], see Fig. 2. There is a clear analogy between a graphene sheet placed inside a dielectric medium and a thin metal waveguide embedded into a dielectric matrix, which also supports localized surface plasmon polaritons. Assuming this analogy, we may expect that a periodic lattice of graphene sheets may behave like a hyperbolic medium due to the coupling between the surface plasmons localized at the individual graphene sheets. Importantly, surface plasmons in graphene have low losses and strong localization in the THz region. Indeed, as we demonstrate in this work, a periodic structure of graphene layers creates a special type of metamaterial with strong nonlocal response and hyperbolic properties of its dispersion curves for TM-polarized waves in the THz frequency range and superior characteristics such as a giant Purcell effect and tunability by a gate voltage or magnetic field. Although hyperbolic metamaterial for the THz range can be realized by using conventional metal-dielectric structures, large negative permittivity of metals significantly limits the increase of the radiation efficiency of the emitters placed in such structures.

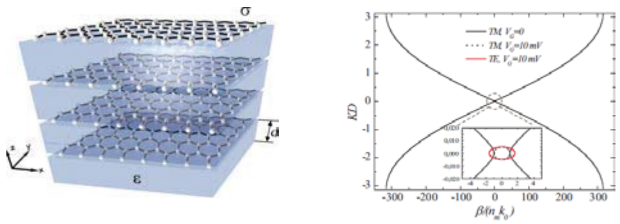

Fig 1. Left: schematic of the structure; Right: Isofrequency curves for different control voltage

The dispersion properties of the structure are defined by the graphene conductivity σ(ω) which depends on the chemical potential μ. Thus, changing μ with the external gate voltage we can tune the isofrequency contours of the metamaterial. For example, for the chemical potential $\mu = 44$ meV, the isofrequency curves of TM polarized waves are elliptic whereas they become hyperbolic for the gate voltage to 10 mV (see Fig. 1, right).

We also present the study of the *nonlocal response* of such a multi-layer structure, as well as the tunability by external *magnetic field*. In the presence of a strong magnetic field the longitudinal and Hall part of graphene conductivity are governed by the electron transitions between the discrete Landau levels. We find that, although the imaginary part of the longitudinal conductivity is negative and we would expect the elliptic contours for both the eigenmodes, the coupling via the Hall conductivity term changes the properties dramatically, and the isofrequency contours have a complicated shape, which is neither elliptical nor hyperbolic [5].

We analyse the *Purcell factor* in the structure, and predict that it can achieve giant values. This suggests that graphene-based hyperbolic metamaterial is an excellent candidate for boosting THz emission by sources placed on a surface of such a medium [5].

References

[1] R. R. Nair, P. Blake, A. N. Grigorenko, K. S. Novoselov, T. J. Booth, T. Stauber, N. M. R. Peres, and A. K. Geim, Science **320**, 1308 (2008).

[2] Z. Fei, A. S. Rodin, G. O. Andreev, W. Bao, A. S. McLeod,M. Wagner, L. M. Zhang, Z. Zhao, M. Thiemens, G. Dominguez, M. M. Fogler, A. H. Castro Neto, C. N. Lau, F. Keilmann, and D. N. Basov, Nature (London) **487**, 82 (2012).

[3] M. L. Nesterov, J. Bravo-Abad, A. Yu. Nikitin, F. J. Garcia-Vidal, and L. Martin-Moreno, Laser Photonics Rev. 7, L7 (2013).

[4] D.A. Smirnova, A.V. Gorbach, I.V. Iorsh, I.V. Shadrivov, and Yu.S. Kivshar, Phys. Rev. B **88**, 045443 (2013).

[5] I.V. Iorsh, I.S. Mukhin, I.V. Shadrivov, P.A. Belov, and Yu.S. Kivshar, Phys. Rev. B 87, 075416 (2013).