Graphene plasmons for couplers and hyperbolic metamaterials

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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.

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.

![Image](image_url)

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 $\sigma(\omega)$ which depends on the chemical potential $\mu$. Thus, changing $\mu$ 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