Efficient modelling of graphene-based optical devices

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Abstract
In the last years the unique optical properties of graphene have attracted the attention of the scientific community, and novel graphene-based photonic, plasmonic and optoelectronic devices have been proposed for a plethora of applications [1, 2]. In this framework, numerical and analytical modelling play a crucial role both for design and analysis purposes. As a matter of fact, well-established models for the complex bi-dimensional linear conductivity of graphene have been reported in the literature (see e.g. [3, 4]), and a strong third-order optical nonlinear response has also been predicted both theoretically and experimentally [5, 6]. Nevertheless the analysis of graphene-based optical devices remains quite challenging from the numerical point of view. Indeed, it was demonstrated that graphene layers can be accurately modeled in conventional full-wave solvers by treating them as volumetric media with known conductivity and proper atomic thickness (< 1 nm) [7, 8], but the required fine discretization of these ultra-thin layers results in a huge computation burden.

In order to overcome this limitation, a different and more efficient approach to this kind of problem has recently been proposed. In fact, it was demonstrated that all the effects induced by the presence of graphene layers embedded in dielectric media can be modeled by discontinuities of the magnetic field which take into account the surface currents flowing on the graphene layers. In this way, the whole analysis is greatly simplified and a more relaxed discretization step can be used. By applying this technique, amplitude equations for surface plasmons in graphene have been derived [9], and the peculiar properties of directional couplers composed of a pair of graphene layers have been thoroughly studied, both in the linear [10] and in the nonlinear regime [11]. In particular, in Ref. [10] we have calculated the dispersion relations of the supermodes of a symmetric graphene plasmonic coupler by illustrating a procedure which allows to treat the more general case of asymmetric structures.

Graphene layers can also be sandwiched within conventional slab waveguides in order to electrically tune the optical properties of these structures. In this context, we have demonstrated that also the nonlinear phase shift which is induced by the strong third-order nonlinearity of graphene can be incorporated into a boundary condition for the tangential magnetic field, and we discussed the existence of nonlinear modes sustained by graphene layers in dielectric waveguides [12]. Moreover, we have shown that the beat length of dielectric couplers can be controlled by inserting graphene layers in the middle of those structures and then tuning the bias voltage in order to vary the dielectric constant of graphene, thus shifting only the effective index of the even supermode [13].

Last, but not least, we have recently proposed to exploit the idea of modelling the graphene as a purely bi-dimensional sheet which imposes a boundary condition on the magnetic field to realize a novel ultra-fast field propagator tailored for graphene-based devices [14]. The algorithm is derived from the well known Beam Propagation Method (BPM), which has been widely used in the last decades for the analysis of wave propagation in photonic devices. The key point of the method is the finite-difference formulation of the second-order derivative, which allows to discretize the discontinuous magnetic field by including in the diffractive operator all the effects which stem from the presence of the graphene layers, thus avoiding to resort to sub-nanometer sampling steps. The novel BPM has been validated first by demonstrating the undistorted propagation of the even and the odd supermodes of the graphene coupler described in [10, 11], as it is possible to verify in Fig. 1. Then, a single waveguide has been excited and the field evolution along the coupler has been evaluated by propagating the input field with the reformulated BPM technique. In Fig. 2 we demonstrate the high tunability of this kind of structure by reporting results obtained by slightly varying the chemical potential of the two layers. In Fig. 3 a systematic comparison between the beat length calculated by using the BPM and analytical results obtained from the solution of the dispersion relations is depicted. The excellent agreement between numerical and analytical results constitutes a strong validation of the proposed technique.

The results that we illustrate are fundamental to show that the novel BPM algorithm allows ultrafast and accurate analysis of complex photonic devices wherein graphene layers are introduced in order to exploit the high tunability of their optical parameters. These findings open the way to the realization of a brand new class of field propagators specifically tailored for the analysis of graphene-based structures.

References

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Figures

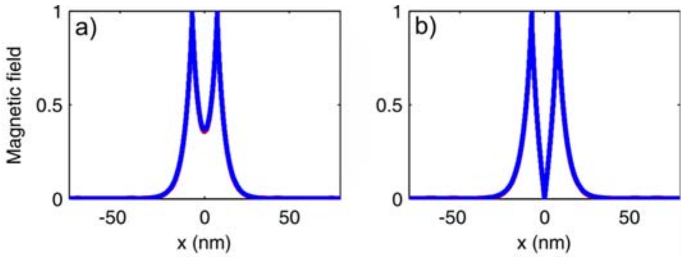

Fig. 1. Magnitude of the magnetic field at the input of the coupler (blue lines) and after BPM propagation (red lines). Blue and red lines are almost overlapped. a) Even supermode. b) Odd supermode.

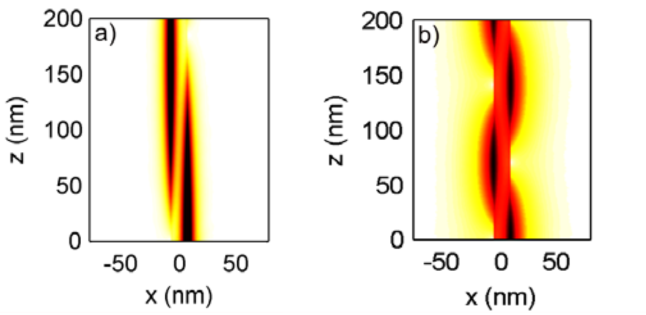

Fig. 2. Field evolution along the coupler evaluated by using the BPM algorithm when chemical potential is μ_c = 0.1 eV (left) and μ_c = 0.16 eV (right).

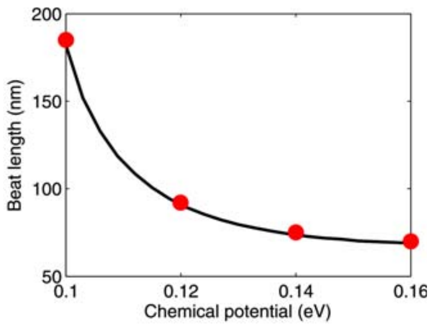

Fig. 3. Beat length of the coupler as a function of the chemical potential evaluated from BPM simulations (red circles) and from the dispersion relations of the supermodes (solid line).