Tunable Graphene-Based Mode Converters and Optical Diodes

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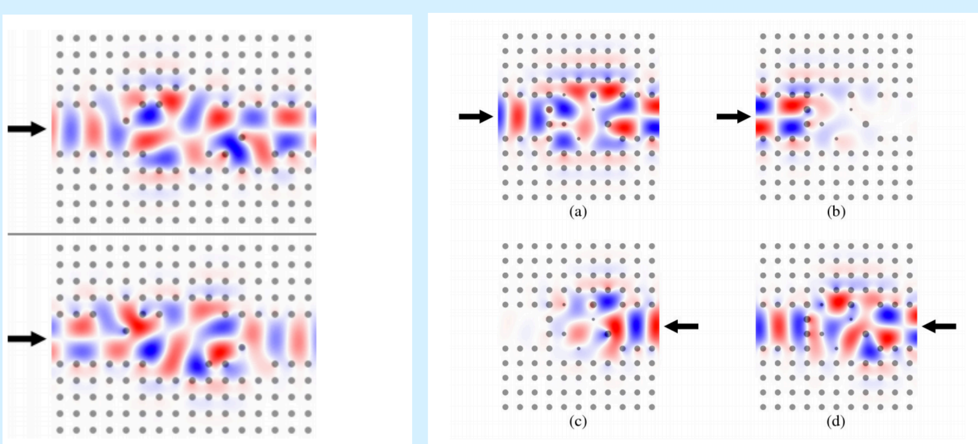
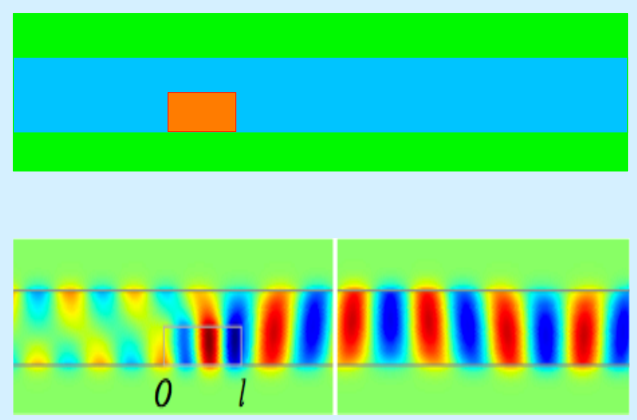
Abstract

We introduce compact tunable spatial mode converters for parallel-plate waveguides consisting of two graphene monolayers operating in the mid-infrared wavelength range. We show that such structures can also be used to design graphene-based optical diodes.

Introduction



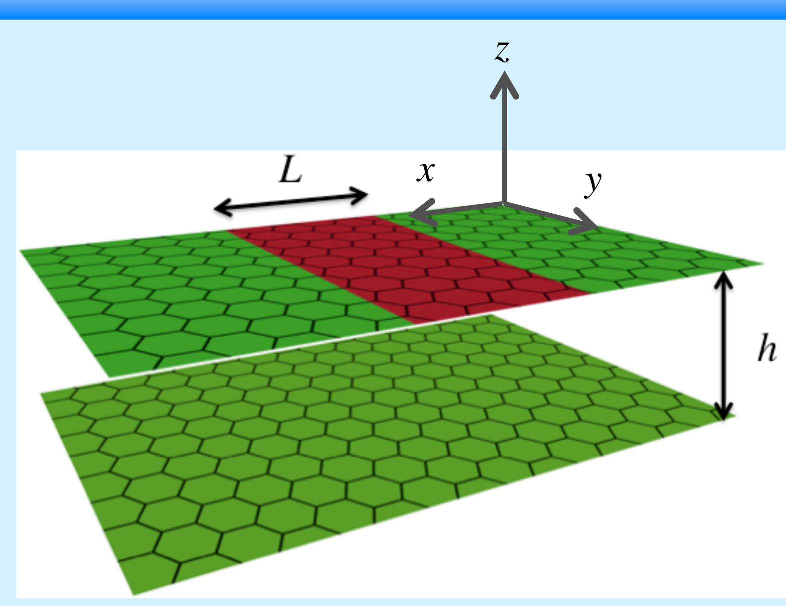
V. Liu et al., Opt. Express, 20, 28388-28397 (2012).



X. T. Kong et al., Opt. Express, 21, 9437-9446 (2013).

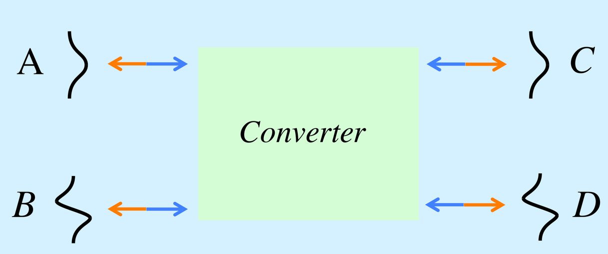
- Manipulation of optical spatial modes in integrated photonic circuits has significant importance due to its potential applications in mode-division multiplexing, efficient waveguide coupling, all-optical logic gates and diodes.
- Many mode converters based on different nanostructures including photonic crystal, silicon, metal-insulator-metal (MIM), and nano-wire structures were proposed and their connections to multiplexing and all-optical diode were studied.
- The multi-mode devices employed in these proposed structures make the mode isolation possible without violating reciprocity.

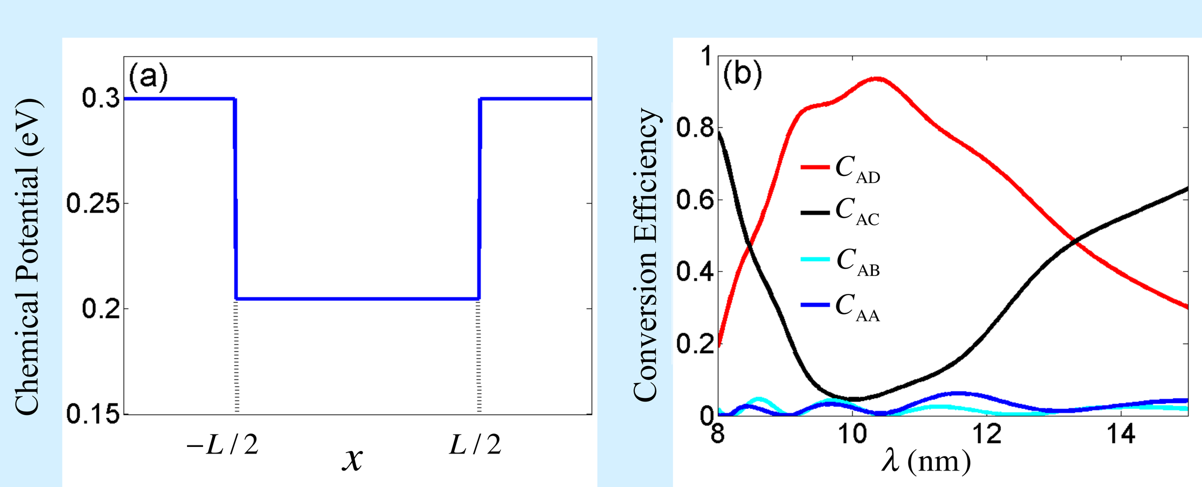
Mode Converter with Non-modulated Chemical Potential



- Our design consists of two layers of graphene that are brought close together. Due to the proximity of the layers, their modes couple. The parallel-plate graphene waveguide is capable of supporting two modes: symmetric (even) and anti-symmetric (odd) mode.
- The principle of the device operation is based on the fact that the odd and even modes can be thought of as in-phase and out-of-phase interactions, respectively, between the surface plasmons propagating on the upper and lower graphene layers. Assuming that the coupling between the two layers is weak, to convert one mode into the other, one needs to create an odd multiple of π phase shift between them. To achieve the required phase shift, we modify the chemical potential (μ_c) on a strip on one of the graphene layers by applying an external voltage or by chemically doping it.

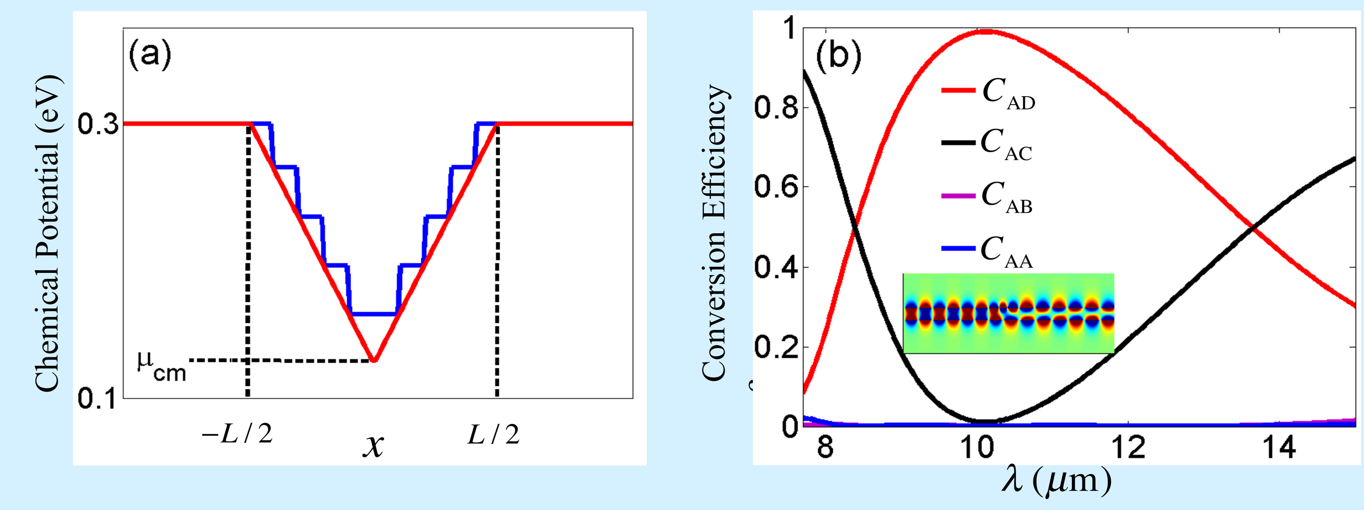
Conversion Efficiency of the Mode Converter with Non-modulated Chemical Potential





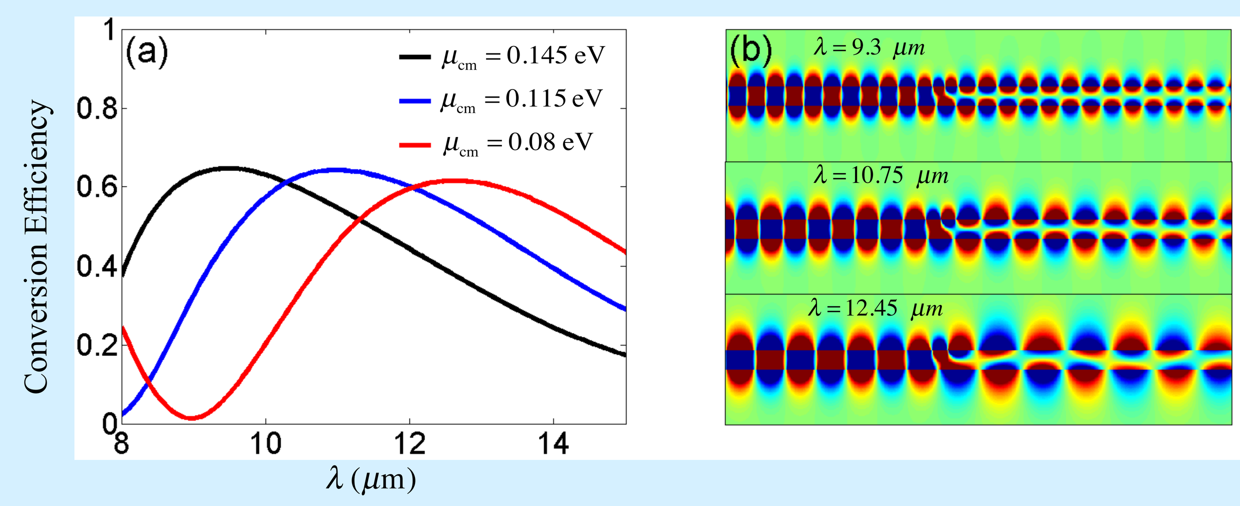
- The scattering matrix of the converter (S), relates the amplitudes of the outgoing modes to the amplitudes of the incoming modes. Since we are interested in the power conversion between different modes, we also define $C_{ij}=|S_{ij}|^2$. Thus, the elements of matrix C represent the power coupling efficiency between different modes.
- For an ideal converter, the anti-diagonal elements of matrix C are one, while the rest of the entries are zero.
- For the lossless structure with the depicted chemical potential (Fig. a), the anti-diagonal elements are shown above (Fig. b). It is observed that at wavelength λ=10.2 μm, the device is very close to an ideal mode converter. However, due to the abrupt change in chemical potential, it suffers from reflection. Moreover, it is also observed that around 4 % of the input power is coupled into the same mode (C_{AC}).

Mode Converter with Modulated Chemical Potential



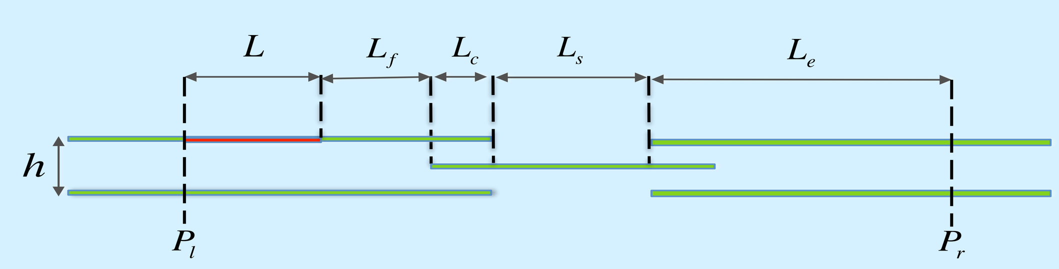
- In order to solve the problems regarding reflection (C_{AA}, and C_{AB}) and conversion into the wrong mode (C_{AC}), we modulated the chemical potential and instead of changing it abruptly, the change is introduced gradually as shown above (Fig. a).
- Modulating the graphene strip has two benefits: first, it reduces the reflection, therefore C_{AA}, and C_{AB} are reduced to almost zero. Second, since reducing the chemical potential decreases the coupling between sheets, modulating the chemical potential helps the conversion process and reduces C_{AC} to almost zero.

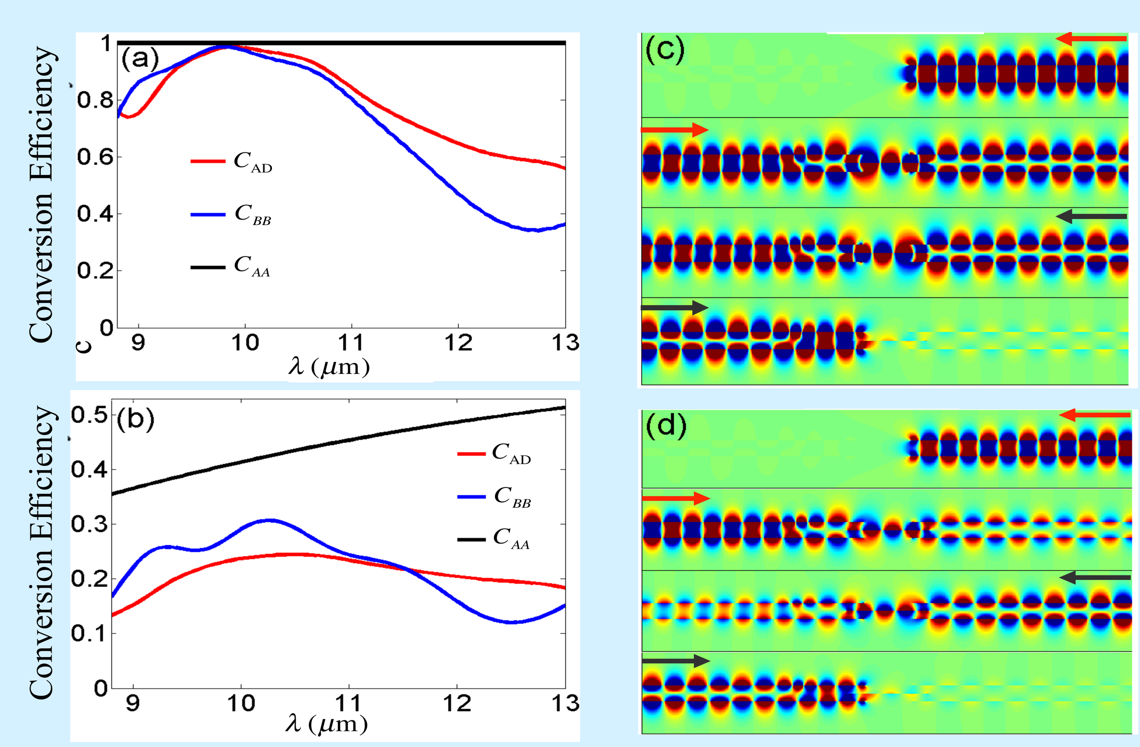
Including Loss



- We started with lossless graphene layers to design the mode converter and, after optimizing the parameters of the device, here the loss is included. To include the effect of loss, the carrier relaxation time previously assumed to be infinite in the lossless case is now included via the equation $\tau=\mu\mu_c/ev_f^2$, where, v_f =10^6 ms^{-1} is the Fermi velocity, μ =1 m/Vs is the carrier mobility and μ_c is the chemical potential. Figure (a) shows the conversion efficiency for three different structures with different modulation parameters and Fig. (b) displays the field profiles of H_z at the wavelength of optimum conversion for the converters with μ_{cm} = 0.145 eV (top figure), μ_{cm} = 0.115 eV (middle figure), and μ_{cm} = 0.08 eV(bottom figure).

Optical Diode





- An ideal optical diode is a device that allows the transmission of one mode in one direction, while entirely reflects the other mode entering the device from the same direction. In the ideal diode, if a mode is completely transmitted in one direction, it is completely reflected in the other direction. For an ideal diode, depending on the position of the converter, the only non-zero entries of the matrix C are C_{AD} =C_{BB} = C_{CC} = C_{DA} =1, if the converter is placed on the left side, or C_{CB}= C_{DD} = C_{AA} = C_{BC} =1, if the converter is placed on the right side. Furthermore, the symmetry and reciprocity of the structure require that C_{BC}= C_{AD}.
- Our proposed device consists of two sections, the converter, shown in the schematic in red color, and the coupler, the middle single-layer sheet. The principle of device operation is simple. Due to mode profile mismatch, only the odd mode can couple to the middle layer. Placing the converter only on one side (left) along with the fact that only the odd mode can couple to the middle layer, enables the device to behave as an optical diode.
- Figures (a) and (c) show the conversion efficiency and H_z profiles of the device, respectively, for the lossless case. Figures (b) and (d) show the performance of the device after including loss.