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 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.

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) on a strip on one of the graphene layers by applying an external voltage or by chemically doping it.

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!S!C. 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 zero, 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!C).

The efficiency of the mode converter (Fig. 2) is given by the conversion efficiency at frequency ω, which is the ratio of the output power to the input power. For an ideal mode converter, there is therefore a symmetry in the S-matrix between the left-to-right conversion, and the right-to-left conversion. (This specific desired symmetry for such an ideal mode converter is preserved under the 20 possible lattice sites within the coupler region.)

In order to solve the problems regarding reflection (C!C and C!C) and conversion into the wrong mode (C!C), 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!C and C!C 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!C to almost zero.

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