Design of a High-Speed Graphene Optical Modulator on a Silicon Slot Waveguide

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Abstract: In this paper, we propose a way to utilize the silicon slot waveguide structure to create a high speed, low power consumption and low insertion loss graphene optical modulator. The active region of the modulator is assumed to be a two graphene layer capacitor structure and the proposal is supported by numerical simulations of absorption.

1. Introduction

Graphene has, for some time, sparked an interest in photonics due to its large light matter interaction. That interest is specifically high in graphene optical modulators. The interest on modulators is due to the fact that the absorption of graphene can easily be switched in a capacitor-like structure where the graphene's Fermi level can be controlled through electrical doping and Pauli blocking can be achieved.

The main issue with graphene based modulators is that, so far, they have been limited in speed. In this paper, we propose the utilization of silicon slot waveguides as the underlying light guiding structure to enable high speed and low insertion loss operation.

2. Modulator's principle of operation

The schematic of the modulator is presented in Fig. 1. It is consisted of a silicon slot waveguide as a guiding medium with a two layer graphene capacitor on the top [1]. The structure is a vertical slot, so the slot effect is observed for the TE mode, which implies this modulator is polarization dependent.

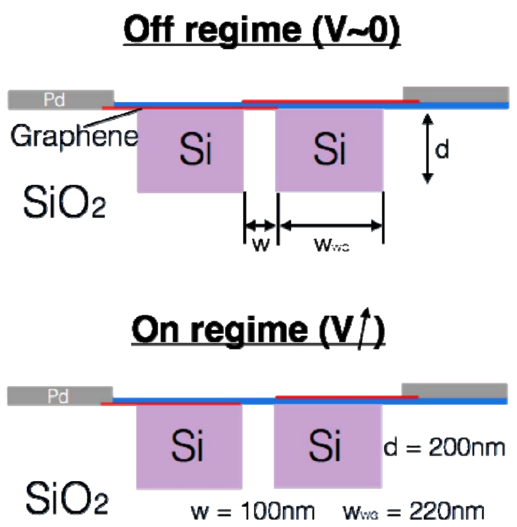

Fig. 1 Scheme and the principle of operation of the graphene modulator on a silicon slot waveguide. Red lines represent "absorbing" graphene – when the voltage is applied the overlapping region becomes transparent.

The basic principle of operation of the modulator, and the reason for the increase in speed, is based on the idea that we introduced previously – to have the graphene electrodes partially overlap [2]. As the speed of the modulator is defined by its RC constant, reducing it would result in a significant increase in the speed of the device (and the decrease in power consumption). It is generally assumed that the main way of increasing the speed of the modulators is to reduce the resistance, as it is a very fabrication dependent parameter, however the approach introduced here is based on the reduction of the capacitance. As explained in [2], when the graphene electrodes are partially overlapped the effective width of the capacitor is the width of the overlapping region, and as the capacitance is directly proportional to the width of the capacitor, potentially great reductions in the capacitance can be obtained.

The main problem with the partial overlap, is that the areas of graphene which are not overlapped will also not experience any electrical doping, which effectively means their absorption will not be switched. Since their absorption is not switched, they constitute insertion loss. Because this insertion loss constraint, the impact of the partial overlap in Ref. [2] on speed has been limited. However, in the structure proposed in this paper (Fig. 1), by utilizing the fact that the most of the optical power is constrained to the slot region, we can simply overlap the graphene electrodes around that region, and switch graphene where the most absorption is occurring. This significantly reduces the insertion loss and increases the speed of the device.

It is important to note that the partial overlap will also increase the sheet resistance in the area around the capacitor, but as the electrodes cannot be very close to the waveguides generally (so they wouldn't interfere with the optical mode), the increase in sheet resistance is negligible with respect to the decrease in capacitance.

3. Numerical Results and Discussions

To clarify the principle of operation of the modulator we provide numerical results in this chapter and further discussions. In all simulations, the parameters have been chosen as in Fig. 1, the dimensions of the slot waveguides have been chosen as the ones which are feasible to fabricate, while the modulator structure has been chosen as in previous work [2]. Fig. 2 shows the optical mode of the graphene covered waveguide.

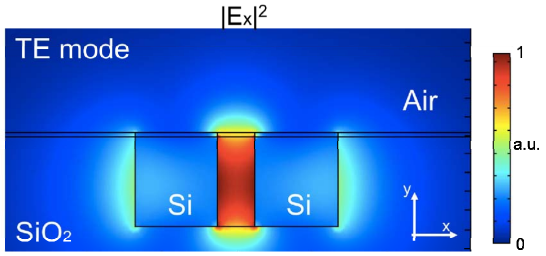

Fig. 2 Optical mode (TE) of the graphene modulator based on a silicon slot wavebuide (for the mode we chose d=240nm).

The mode in Fig. 2 (and results in Fig. 3) has been calculated using the COMSOL Multiphysics simulation software, with graphene taken into account directly through its dynamic conductivity and surface currents in the magnetic field boundary condition [3]. Utilizing this method, we can obtain the complex effective refractive index of the mode, from which imaginary part we can infer the graphene induced absorption.

From Fig. 2, we can observe that the most of the mode is confined to the central region due to the large index mismatch and the fact that the TE mode dominant electric field is perpendicular to that boundary. In our simulations, we assume that the slot is consisted of silica, although air slots would yield even better results (air slots are even feasible fabrication wise – we are assuming a planarizied waveguide structure which needs to be done by additional deposition of oxide. When that happens, the slot will most probably not be deposited by oxide and will remain an air slot.)

Fig. 3 shows the usefulness, and novelty of our proposal with respect to the absorption and insertion loss. We can observe that for feasible slot widths (around 100nm) total graphene induced loss is almost three times as big as the insertion loss, which results in significant modulation depth. Multiple calculations have been conducted for different slot widths and graphene conditions (Fig. 1, on/off stage) providing results presented in Fig. 3. We can observe that due to the slopes of the total and insertion losses there is a peak modulation depth at 100nm which is useful in designing final devices.

It has been discovered previously [4] that graphene, when it covers a silicon slot, has an amplified absorption in comparison to regular waveguide. This is attributed to very high mode confinement in the slot region. In this work, we propose the utilization of the slot in creating a high-speed device.

Results in Fig. 3 show the passive characteristics of the modulator, and the feasibility of using the partially overlapped graphene electrode design without inducing too much insertion loss – there is still a need to characterize the dynamic properties of the devices.

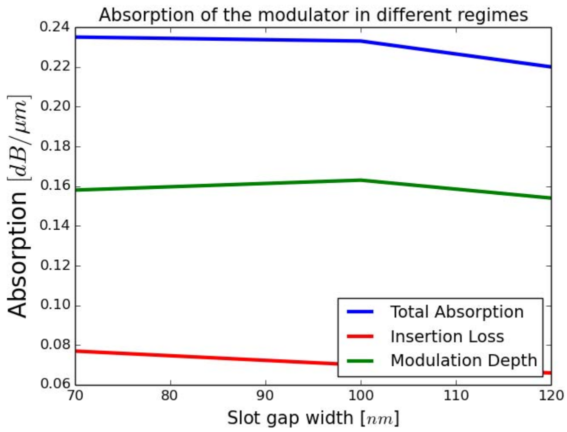

Fig. 3 Total absorption (blue), insertion loss (red) and calculated modulation depth for the proposed graphene modulator. The slot width w is varied while other parameters are chosen as in Fig. 1.

As it is very difficult to estimate the resistance numerically, we will just state that with the partial overlap we can reduce the width of the capacitor by as much as 6 times to the current designs, which, theoretically, should yield an increase in the speed of the same magnitude. Realistically, we could expect 2-3 times order of increase due to the parasitic increase in the resistance and the imperfection of the fabrication process. However, as the current record of graphene modulator speed is 30GHz [5], increase of three times could provide an industry ready modulator.

4. Conclusion

In this paper, we presented a novel idea of how we can utilize the slot waveguide structure to obtain a very efficient graphene modulator. We emphasized the results with numerical calculations and paid attention to fabrication feasibility.

References

[1] M. Liu, et al, "Double-Layer Graphene Optical Modulator," Nano Lett., 12 (3), 1482–1485, 2012.
[2] G. Kovacevic and S. Yamashita, "Design optimizations for a high-speed two-layer graphene optical modulator on silicon," IEICE electronics express, Vol 13, no 44, 2016.
[3] G. Kovacevic and S. Yamashita, "Waveguide design parameters impact on absorption in graphene coated silicon photonic integrated circuits," Optics Express, Vol. 24, Issue 4, 3584-3591, 2016.
[4] J. Wang, et al, Nanoscale, "High-responsivity graphene-on-silicon slot waveguide photodetectors," Vol. 8, 13206-13211, 2016.
[5] C. Phare, M. Lipson, et al, "Graphene electro-optic modulator with 30 GHz bandwidth," Nature Photonics 9, 511–514, 2015.