# Compact high-speed electro-optic modulator based on a silicon photonic-crystal nanobeam cavity with gated graphene

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***Abstract* — We propose and numerically study a compact high-speed electro-optic modulator by gating graphene on a silicon photonic-crystal nanobeam cavity. 13.5-dB modulation depth, 133-GHz operation speed, and 270-nm FSR are achieved in simulations.**

***Keywords* — electro-optic modulator, graphene, silicon photonic-crystal nanobeam cavity.**

## I. Introduction

Graphene, the single layer of carbon atoms packed into a honeycomb lattice, has drawn much attention as an optoelectronic material [1]. The introduction of graphene as an active medium for electro-optic (EO) modulators is promising since graphene exhibits high carrier mobility and gate-controllable broadband absorption. Graphene EO modulator based on silicon waveguide structure has been demonstrated [2]. However, long physical length of the silicon waveguide is required to achieve high modulation depth, as light needs to travel a long distance to overlap with the graphene. Large device size limits applicability to large-scale on-chip integration. Therefore, graphene-silicon microring modulators have been investigated to greatly enhance light-graphene interaction and reduce the device footprint [3]. Nevertheless, microring resonators still show hundreds of $\mu m^2$ footprint. Photonic-crystal nanobeam cavity can overcome the limitation, as it can achieve ultra-compact device footprint and large free spectral ranges (FSRs) [4]. A single resonance on a wide spectral window allows other optical carriers in wavelength-division multiplexing (WDM) systems to pass through the device without being affected.

In this paper, we present an ultra-compact high-speed EO modulator on a silicon-on-insulator (SOI) platform, which is implemented by a designed nanobeam cavity coupled to a bus waveguide with gated graphene atop. The proposed device combines the merits of nanobeam cavity and graphene in a single device. Benefiting from the fast and strong EO effect of graphene on the ultra-compact photonic-crystal nanobeam cavity with large FSR, high-speed and efficient modulation can be achieved on a wide spectral window. FDTD simulation results show that our proposed modulator can provide a modulation depth of ~13.5 dB, a device speed of 133 GHz, and a large FSR of 270 nm in a small modal volume.

## II. Operation Principle and Device Fabrication

The proposed modulator is schematically depicted in Fig. 1(a), which consists of a designed nanobeam cavity coupled to a bus waveguide with graphene atop on a SOI wafer. As shown in the cross-section of the device in Fig. 1(b), an n-type doping region is formed by patterned ion implantation in the 50-nm-thick silicon slab. 7-nm-thick $Al_2O_3$ as the gate dielectric material is deposited on part of the silicon slab and nanobeam cavity. The chemical vapor deposition (CVD) prepared graphene layer is then transferred onto the $Al_2O_3$ layer. Following these steps, a deep ultraviolet (DUV) photolithography process is used to define the device pattern, which is then etched into the silicon layer by inductively coupled plasma (ICP) etching. The top view of the designed nanobeam cavity is illustrated in Fig. 1(c), which contains reflector and taper sections [5]. The reflectors guarantee that the light be highly reflected within the wavelength range of interest. The taper section is designed to smoothen the reflected optical response, as well as to provide a single resonance within a large spectral window of high reflectivity. The cross-section of the waveguide is 500 nm × 220 nm, and the gap size in the coupling region is 167 nm, which is close to the critical coupling condition. Finally, metal electrodes are applied between the bottom n-type doped silicon slab and the graphene layer. The modulator footprint mostly comes from the electrical contacts and the overall footprint can be possibly down to ~20 $\mu m^2$.

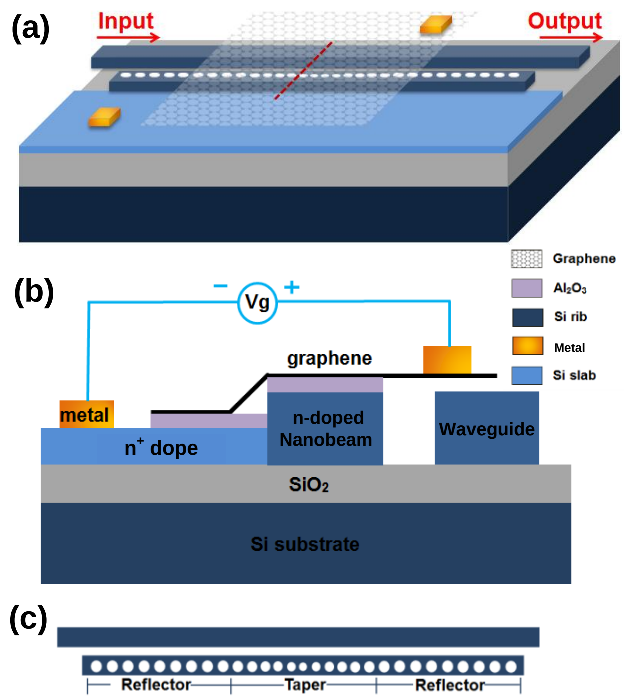


Fig. 1. (a) Schematic perspective view of the proposed EO modulator. (b) The cross section corresponding to the red dashed line in (a). (c) Top-view of the photonic-crystal nanobeam cavity. The cavity is symmetric with respect to its center, both reflector and half of taper sections are identical.

Gate voltage can change the graphene's carrier density, and accordingly shift the Fermi level $E_f$ of graphene. Obtained from the Kubo formula [6], the in-plane permittivity of graphene can be controlled in a wide range through the variation of Fermi level, which is depicted in Fig. 2(a). Note that the permittivity of graphene varies very fast with a dip in the magnitude curve at $E_f$ = 0.51 eV, where "dielectric graphene" changes to "metallic graphene". The effective mode index $n_{eff}$ variation for the proposed device calculated from the Eigen-mode solver of the

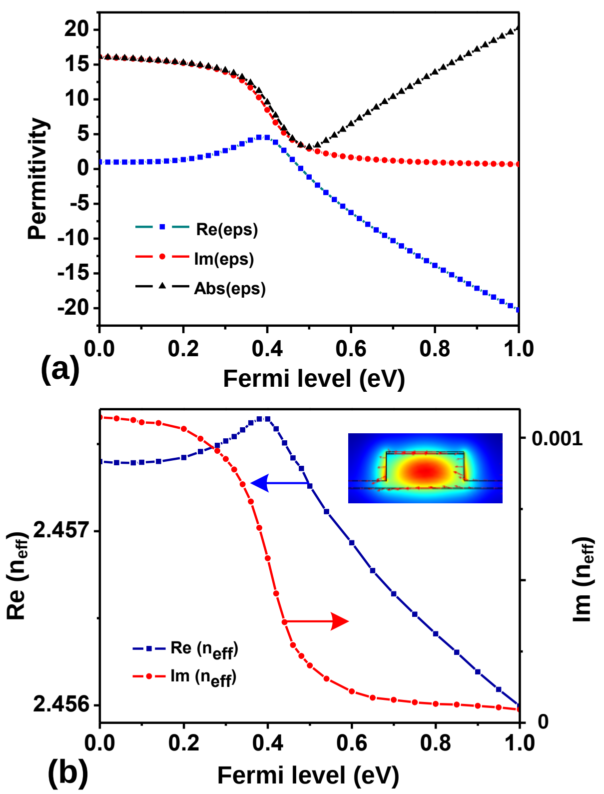


Fig. 2. (a) Real part, imaginary part, and magnitude of calculated in-plane permittivity of graphene under different Fermi levels of graphene. (b) The real and imaginary part of effective modal index for TE mode of the proposed device with graphene as a function of Fermi level. The inset is the optical profile of TE mode. All the simulations are performed at 1550 nm.

commercial software COMSOL is shown in Fig. 2(b), and the electric field distribution for transverse electric (TE) mode is displayed in the inset of Fig. 2(b). The variation of the effective mode index is similar to that of the graphene's permittivity. The effective index for TE mode of the proposed structure based on graphene is changed evidently due to the enhanced light-matter interaction, indicating high modulation ability.

## III. Nanobeam Cavity and Its Performance

Fig. 3(a) shows transmission spectra of the proposed device at different Fermi levels. It can be seen that different resonance notches vary with different Fermi levels, so it can be used in amplitude modulation. Amplitude modulation depth as large as ~13.5 dB at $\lambda_0$ = 1549.2 nm is achieved. By shifting the Fermi levels from 0.4 eV to 1 eV, the real part of effective mode index of the proposed device experiences a change of 0.0164, leading to a 1.09-nm resonance wavelength blueshift, and the increased Q factor can be explained by the decreased imaginary part of $n_{eff}$.

FSR and modulation speed are important metrics to measure the performances of EO modulators in WDM systems. As shown in Fig. 3(b), our proposed device provides a single resonance within a broad operation spectrum that ranges from 1.4 to 1.67 μm at $E_f$ = 1 eV with a high extinction ratio of ~15 dB. The speed of the modulator is limited by RC constant, and a low capacitance is the key for low energy and high speed operations [7]. In our device, the graphene resistance is around 20 Ω and the capacitance is ~60 fF, leading to a modulation speed of ~133 GHz.

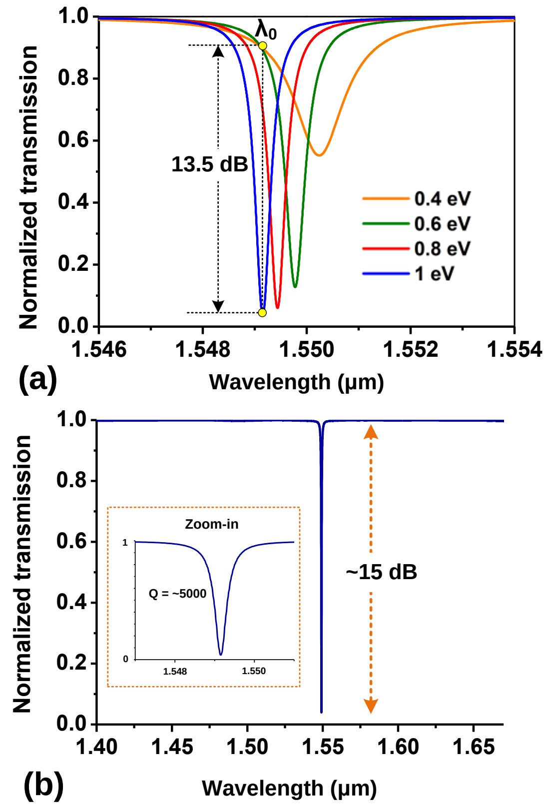


Fig. 3. (a) Normalized transmission spectra at different chemical potentials of the proposed device. (b) Normalized transmission spectrum at 1 eV chemical potential of graphene, ranging from 1400 nm to 1670 nm; the inset is the zoom-in view of the spectrum, ranging from 1545 nm to 1553 nm.

## Conclusion

In conclusion, we have proposed and numerically demonstrated an active electro-optic modulator based on a silicon photonic-crystal nanobeam cavity with gated graphene atop. Through gate tuning of the Fermi level in graphene in the proposed modulator, amplitude modulation with a depth of ~13.5 dB is achieved and the modulation speed and FSR are up to 133 GHz and 270 nm respectively. Its footprint is significantly reduced to fit large-scale on-chip integration.

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