Metal-clad-suspended self-biasing graphene modulator with tunable figure of merit

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Abstract In this letter, a research on the metal-clad-suspended self-biasing graphene modulator is conducted theoretically. The results reveal a higher light–graphene interaction for the more compact modulator. In addition, when the light–graphene interaction is enhanced, the light–metal interaction is also higher, which causes larger insertion loss and makes the figure of merit (FOM) lower. The length of π -phase shift is reduced to 6.35 μm for the Mach–Zehnder modulator, which is the smallest size achieved up to date. The modulator’s FOM can be tuned by changing the air gap (d) between the moveable metal plates and the suspended structure. In the case when this air gap increases, the configuration represents closer fundamental limits design. Moreover, the cut-off mode is discussed, and it has potential to be used in the tunable filter application. This tunable configuration of modulator is believed to have potential that can pave the way to design tunable light–matter interaction device and has evaluated for the near fundamental limits design.

Keywords Graphene modulators · Figure of merit · Suspended · Filter

Introduction

Graphene modulators show greater application prospect than traditional silicon modulators since it was firstly demonstrated and reported in 2011 [1]. This is because the fundamental limits [2] of graphene modulator are much

further than that of the modulator made by traditional materials such as silicon. Graphene has much broader and deeper tunable absorption [3] and ultrahigh mobility [4, 5] in the wide band wavelength from visible light to THz band for the interested electro-modulation and absorption. Till now, all the figure of merits (FOMs) of modulator made by graphene, such as modulation depth, modulation speed, operation bandwidth, footprint, and modulation efficiency are much better and far beyond than that of traditional modulators.

In this field, in order to realize near fundamental limits designing, different modulator structures are put forward [6–10]. The main purpose is to enhance the light–graphene interaction. Researchers have found that the symmetrical structure [6, 7] can make the mode with lower insertion loss and higher modulation depth, so the light–graphene interaction is enhanced further. The figure of merit (FOM) of graphene modulator is defined as the ratio of modulation depth to insertion loss. And the FOM can be an index of how the design is approaching the fundamental limits (it’s a relation between insertion loss and modulation depth, as described in Ref. [2]) of graphene modulator.

In our recently work [11–13], we have reported the suspended graphene modulators which are already much near the fundamental limits of graphene modulator. The FOMs of these cases are in the order of 2000 [11–13] and the contradiction between modulation speed and modulation efficiency is reduced significantly. These results are contributed by that the devices are very clean and the modes are symmetrical. However, the modulator which is between low design and near fundamental limits design is still a gap which should be addressed.

In this letter, we show how near fundamental limits design happens. Here, a suspended self-biasing graphene modulator with tunable metal cladding is investigated. The

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light–graphene interaction is very complex and can be enhanced and tuned significantly by very small modulation size. The modulation depth and insertion loss are increasing with considered smaller modulation size. The FOM is changeable by different insulator thicknesses and tunable by moveable metal cladding. However, when the modulation size is too small, the mode will be cut-off and the loss is huge. The trade-off between modulation depth and FOM is analyzed and the filter application by cut-off wavelength is also discussed. We find that when the air gap (d) between moveable metal cladding and suspended structure is larger, the design is nearer to the fundamental limits of graphene modulator. However, we can control the tunable light–graphene interaction by smaller air gap (d).

Results and discussions

The structure of metal-clad-suspended self-biasing graphene modulator is shown in Fig. 1a.

For this structure, two monolayer graphene sheets are sandwiched by an insulator slab (here aluminum oxide Al_2O_3 , $\epsilon_1 = 3.06$ at $\lambda = 1.55 \mu\text{m}$). These two graphene sheets are biased by each other and suspended in the air. Two moveable metal plates (here copper is adopted, the permittivity ϵ_3 is got from Drude model) are cladding above or below both sides of the suspended structure. The active area of the modulator includes seven layers: the moveable upper and below metal plates (ϵ_3), the two air gaps (ϵ_2) with distance d is shown in the figure, two graphene sheets (permittivity is $\epsilon_g = i\sigma_g/\omega\epsilon_0\delta$ [14, 15], where the surface conductivity σ_g is calculated from Kubo formula [16], $\delta = 0.33 \text{ nm}$ is the thickness of the monolayer graphene), and the middle insulator slab (Al_2O_3) with thickness w . Here the air gap (d) between metal cladding and the suspended structure is tunable by moving the metal plates. The corresponding axis system is also shown in Fig. 1a, the modulator width in y -direction is large enough for the beam width diffraction which doesn't have boundary and can be assumed to be the same as in free-

space. The optical wave (here $\lambda = 1.55 \mu\text{m}$) incidents in z -direction which is perpendicular to x – y plane.

The methodology here is to derive the mode field equations and the dispersion equation of this symmetrical seven-layer structure for TE mode which has been used and discussed in detail in reference [12]. This is the well-known two-dimensional analysis [17].

Figure 2 shows the mode power attenuation (MPA, α) as a function of chemical potential of graphene (μ_c) when insulator (Al_2O_3) slab thickness is $w = 100 \text{ nm}$ and air gap width is $d = 500 \text{ nm}$ (black solid line), 300 nm (red dashed line) or 250 nm (blue dotted line) at $\lambda = 1.55 \mu\text{m}$.

There shows an off-state MPA (α_{off}) and an on-state MPA (α_{on}) and a modulation depth of $\Delta\alpha = \alpha_{\text{off}} - \alpha_{\text{on}}$. At the absorption threshold point of graphene ($\mu_c = 0.4 \text{ eV}$ here), the mode transfers from off-state to on-state when the chemical potential is slightly higher. This is because when the chemical potential is lower than half photon energy (0.4 eV for $\lambda = 1.55 \mu\text{m}$), the graphene causes interband absorption, otherwise, only intraband absorption happens which causes very small loss.

Here, the insulator slab has a thickness of $w = 100 \text{ nm}$. However, when the air gap width changes from $d = 500 \text{ nm}$ to $d = 250 \text{ nm}$ the modulation depth increase from $0.4339 \text{ dB}/\mu\text{m}$ ($\alpha_{\text{off}} = 0.4368 \text{ dB}/\mu\text{m}$, $\alpha_{\text{on}} = 0.0029 \text{ dB}/\mu\text{m}$ for $d = 500 \text{ nm}$) to $1.2388 \text{ dB}/\mu\text{m}$ ($\alpha_{\text{off}} = 1.2754 \text{ dB}/\mu\text{m}$, $\alpha_{\text{on}} = 0.0366 \text{ dB}/\mu\text{m}$ for $d = 250 \text{ nm}$), respectively. The light–graphene interaction is much better enhanced when the air gap width d is smaller. The normalized insertion loss is α_{on} , so the FOM of this modulator can be defined as [8]:

$$\text{FOM} = \Delta\alpha/\alpha_{\text{on}} \quad (1)$$

For $d = 500 \text{ nm}$ and $d = 250 \text{ nm}$, we get the value of FOM of 150 and 34, respectively. So when the light–graphene interaction is enhanced, we get the modulation depth but loss the FOM for much larger insertion loss caused by the metal plates (larger light–metal interaction).

From the inset of Fig. 2, the corresponding mode index (N_{eff}) for each case can be noted. When d is smaller, N_{eff} is

Fig. 1 **a** Cross section schematic of the structure of metal-clad-suspended self-biasing graphene modulator. **b** Schematic of Mach–Zehnder modulator

Fig. 2 MPA α of the modulator is gotten as a function of chemical potential μ_c when $w = 100$ nm and $d = 500$ nm (black solid line), 300 nm (red dashed line) and 250 nm (blue dotted line) at wavelength $\lambda = 1.55$ μm . The inset shows the corresponding effective refractive index (N_{eff}) of the mode as a function of μ_c (color figure online)

much lower than 1 for much larger light–metal interaction. The change of mode index (ΔN_{eff}) is 0.04365, 0.07736, and 0.12200 for $d = 500$ nm, 300 nm, and 250 nm respectively. If two of this modulator are used as two arms of Mach–Zehnder (M–Z) modulator, the π -phase shift length will be only 17.75 μm , 10.02 μm , and 6.35 μm accordingly at $\lambda = 1.55$ μm . This is a great improvement for M–Z modulator. The schematic of the M–Z modulator is shown in Fig. 1b. Two arms of this waveguide are used: One is the reference arm (modulator guide 1) with a fixed applied voltage (chemical potential); one is the modulation arm (modulator guide 2) with a changeable applied voltage (information signal). The carrier wave is split at the left port and converged at the right port.

Figure 3 shows the modulation depth and FOM as a function of insulator thickness w when air gap width $d = 500$ nm (a) and 300 nm (b) at wavelength $\lambda = 1.55$ μm :

Fig. 3 Modulation depth (black solid line) and FOM (red dashed line) as a function of insulator thickness w when air gap width $d = 500$ nm (a) and 300 nm (b) at wavelength $\lambda = 1.55$ μm (color figure online)

From Fig. 3, we can see for both cases, the modulation depth decreases and FOM increases as w is becoming larger, so the thinner w can cause higher light–graphene interaction, but it also causes higher insertion loss for higher light–metal interaction. For $d = 500$ nm, the modulation depth is in the scale of 0.54 $\sim$ 0.22 dB/ μm (1.94 $\sim$ 0.24 dB/ μm for $d = 300$ nm) and the corresponding FOM is in the scale of 70 $\sim$ 400 (25 $\sim$ 92 for $d = 300$ nm) when w is changing from 10 to 300 nm (50–300 nm for $d = 300$ nm). Therefore, there is a trade-off between higher modulation depth and higher FOM. If the modulation depth is got, the modulation efficiency will loss for larger insertion loss and the design will be further away from the fundamental limits of graphene modulator. According to our calculation, we find for $d = 300$ nm, the mode is cut-off when w is lower than 50 nm. The cut-off wavelength (λ_c) has a relation of [18]:

$$f_c = \frac{c}{\lambda_c} = \frac{c}{2(n_1 w + 2d)} \quad (2)$$

here $c = 3 \times 10^8$ m/s is velocity of light in vacuum, $n_1 = \sqrt{\epsilon_1}$ is the refractive index of the insulator material ($n_1 = 1.75$ for $\epsilon_1 = 3.06$), $(n_1 w + 2d)$ is the optical interval between two metal plates. From Eq. (2), we can change it to:

$$w_c = \frac{\lambda}{2n_1} - \frac{2d}{n_1} \quad (3)$$

We submit $\lambda = 1.55$ μm , $n_1 = 1.75$ and $d = 300$ nm to Eq. (3), and get $w_c = 100$ nm, which is why when $w < 50$ nm, the loss become huge. When the mode is cut-off, the light–metal interaction will be extremely high which will cause much higher insertion loss and much lower FOM even though the modulation depth may be enhanced.

The applied voltage should be higher (~ 20 V) when Al_2O_3 is used as the gate material. If we use thinner gate material, the modulation depth is enhanced, however, the

FOM will loss as shown in Fig. 3. According to our calculation, if we use high- κ gate material [19], the contradiction between modulation depth and FOM will be reduced significantly. For example, if Ta_2O_5 ($\epsilon_1 = 22$) is adopted as the gate material, we choose $w = 30$ nm, $d = 500$ nm, the applied voltage can be only V_{off} (0.3 eV) = 0.37 V, V_{on} (0.5 eV) = 1.0 V, and the modulation depth is 0.56 dB/ μm with a FOM of 694, which are all much better values. Therefore, high- κ gate material is much better to fabricate this modulator. In this case, we can get an energy consumption as low as ~ 1 fJ/bit according to our calculation.

We get the modulation depth and FOM as a function of air gap width d when $w = 100$ nm at $\lambda = 1.55$ μm , as shown in Fig. 4:

As it can be observed that the modulation depth is much higher at lower d which enhances the light–graphene interaction. However, the light–metal interaction is also enhanced which causes higher insertion loss and lower FOM. Since d is changeable by moving the metal cladding, we can achieve tunable FOM for this modulator. When d is too small, the mode will also be cut-off. From Eq. (2), the relation of cut-off d_c can be derived as:

$$d_c = \frac{\lambda}{4} - \frac{n_1 w}{2} \quad (4)$$

when $\lambda = 1.55$ μm , $n_1 = 1.75$ and $w = 100$ nm, we get $d_c = 300$ nm. Even for lower value of d , the loss will be even high. Therefore, when d is larger, nearer fundamental limits design can be achieved.

In order to get a better knowledge of light–matter interaction, the mode fields of the modulator are calculated as a function of x -axis, as shown in Fig. 5.

It can be observed that the mode confinement will be absolutely better when d is lower. This is because for TE mode, the metal plate will confine the field for it is always

Fig. 4 Modulation depth (black solid line) and FOM (red dashed line) as a function of air gap width d when insulator thickness $w = 100$ nm at wavelength $\lambda = 1.55$ μm (color figure online)

Fig. 5 Mode field distributions as a function of x -axis when $w = 100$ nm, $d = 500$ nm (black solid line); $w = 100$ nm, $d = 300$ nm (red dashed line); $w = 50$ nm, $d = 300$ nm (blue dotted line) at wavelength $\lambda = 1.55$ μm (color figure online)

E-field near at the interface of metal. When w is lower, according to our calculation, we find the mode amplitude (A) in graphene layer is higher (A is 0.948 for $w = 100$ nm, and 0.985 for $w = 50$ nm). As the confinement of the mode will enhance the photon number which interact with graphene and the amplitude in graphene layer may enhance the interaction strength of one photon, the light–graphene interaction will absolutely be enhanced by lower d and lower w . However, the light–metal interaction is also enhanced by lower d and lower w for larger evanescent depth.

The transmittance and the modulation performance are gotten as a function of carrier wavelength according to $T(\lambda) = \text{Exp}[-\alpha L]$ when $L = 5$ μm is the modulator length, as shown in Fig. 6:

For $w = 100$ nm and $d = 500$ nm, the insertion loss can be very low at the interested wavelength ($T_{\text{max}} = 0.995$), but the modulation depth is lower for this case (only $\sim 50\%$). However, for other two cases, the modulation depth can be higher ($\sim 77\%$) but the insertion loss is also higher. When the wavelength is too large, the mode will be cut-off, here we can see the calculated cut-off wavelength is $\lambda_c = 2.68$ μm , 1.89 μm and 1.62 μm for these three cases accordingly. The wavelength which is larger than λ_c will be filtered accordingly. According to Eq. (2), it can be changed to λ_c form as:

$$\lambda_c = 2(n_1 w + 2d) \quad (5)$$

for these three cases, the achieved theoretical cut-off wavelength is $\lambda_c = 2.35$ μm , 1.55 μm and 1.375 μm . The calculation results show slightly red shift but agree with the theory value very well.

The full-wave simulation using commercial software (COMSOL) is conducted, which shows good agreement with

Fig. 6 **a** Transmittance as a function of carrier wavelength when $w = 100 \text{ nm}$, $d = 500 \text{ nm}$ (black solid line); $w = 100 \text{ nm}$, $d = 300 \text{ nm}$ (red dashed line); $w = 50 \text{ nm}$, $d = 300 \text{ nm}$ (blue dotted line), which are all at modulator length $L = 5 \mu\text{m}$ and chemical potential of $\mu_c = 0.4 \text{ eV}$. **(b–d)** are the mode profiles in the

longitudinal direction at different structure parameters: **b** $w = 100 \text{ nm}$, $d = 500 \text{ nm}$ at $\mu_c = 0.5 \text{ eV}$; **c** $w = 100 \text{ nm}$, $d = 500 \text{ nm}$ at $\mu_c = 0.3 \text{ eV}$; **d** $w = 50 \text{ nm}$, $d = 300 \text{ nm}$ at $\mu_c = 0.5 \text{ eV}$ (color figure online)

our calculation results. The mode profiles in the longitudinal transmission direction are shown in Fig. 6b–d. In this simulation, we set insulator permittivity $\epsilon_1 = 3.06$, graphene monolayer thickness $\delta = 0.33 \text{ nm}$, insulator thickness $w = 0.1 \mu\text{m}$ [(b) and (c)] or $0.05 \mu\text{m}$ (d) with a cladding air area of $d = 0.5 \mu\text{m}$ [(b) and (c)] or $0.3 \mu\text{m}$ (d) and modulation length of $L = 5 \mu\text{m}$ at chemical potentials of $\mu_c = 0.5 \text{ eV}$ [(b) and (d)] or 0.3 eV (c). We can see the decay of the mode amplitude is negligible for the case of $w = 0.1 \mu\text{m}$, $d = 0.5 \mu\text{m}$ and $\mu_c = 0.5 \text{ eV}$; however, it is significant for the case of $w = 0.1 \mu\text{m}$, $d = 0.5 \mu\text{m}$ and $\mu_c = 0.3 \text{ eV}$. We can also know the mode is totally cut off for the case of $w = 0.05 \mu\text{m}$, $d = 0.3 \mu\text{m}$ and $\mu_c = 0.5 \text{ eV}$.

Conclusions

In this letter, a theoretical research on the metal-clad-suspended self-biasing graphene modulator has been carried out. The light–graphene interaction can be enhanced by smaller size of this modulator, such as lower insulator slab thickness w

and lower air gap width d . However, the light–metal interaction is also stronger with smaller size which causes larger insertion loss and makes lower FOM. The change of mode index (ΔN_{eff}) can be as high as 0.12200 causing a π -phase shift length of only $6.35 \mu\text{m}$ for M-Z modulator which is the best value up to date. The FOM is tunable by changing the air gap (d) between the moveable metal plates and the suspended structure. When the air gap is larger, this configuration shows nearer fundamental limits design. The mechanism of light–graphene interaction is analyzed by the mode field distribution. Moreover, the cut-off mode is discussed by showing w_c , d_c and λ_c , and the tunable filter application is mentioned. At the end, we show a 2D mode profile in the longitudinal transmission direction by COMSOL simulation, which matches our calculation results. We believe these results are very useful to design tunable light–matter interaction devices and contribute to tunable FOM physics.

In order to get a better knowledge of how nearer fundamental limits of graphene modulator happens, the FOMs of related graphene modulators are summarized as comparison in Table 1:

Table 1 Comparison with other modulators

Refs.	Modulation speed	Extinction ratio	Energy-per-bit	FOM ($\Delta\alpha/\alpha$)	Footprint	Insertion loss
[1]	1.2 GHz	0.1 dB/ μm	NA	NA	25 μm^2	NA
[8]	NA	16.83 dB/ μm	0.08 fJ/bit	72	0.05 μm^2	13.5 dB
[9]	1 GHz	0.16 dB/ μm	1 pJ/bit	NA	40 μm^2	4 dB
[10]	120 GHz	80%	NA	NA	60 μm^2	2.5 dB
[11]	559.2 GHz	0.54 dB/ μm	1.23 fJ/bit	2706	1.5 μm^2	0.002 dB
[12]	759.85 GHz	0.834 dB/ μm	0.61 fJ/bit	2105	0.94 μm^2	0.00166 dB
[13]	54.85 GHz	0.4474 dB/ μm	NA	2480	NA	0.00247 dB
This work	NA	1.2388 dB/ μm	1 fJ/bit	25 ~ 400	NA	0.0029 ~ 0.0366 dB/ μm

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