Abstract We propose and numerically investigate a new modulation principle and method, the gate-voltage-controlled mode-guiding switching/mode-cutoff mechanism, to achieve the modulation/attenuation function. The propagating attenuation of the graphene 2D waveguide as a function of the Fermi level of the cladding is analyzed. Different modes with low or high attenuations in a wide attenuation range have been observed. The proposed structure avoids the patterning on graphene or substrate, thus diminishing the energy scattering on the edges. It also has the advantages of large modulation depth/attenuation range, wide bandwidth, and sub-micrometer chip-length with a nanoscale lateral section, which is promising for future graphene-based integrated photonic devices.

Tunable graphene-based plasmonic waveguides: nano modulators and nano attenuators

Jieer Lao1,∗∗, Jin Tao2,3,∗∗, Qi Jie Wang2,3, and Xu Guang Huang1,∗

1. Introduction

The field of plasmonics has become one of the exciting research focuses, which enables one to build nanostructures and nanodevices at subwavelength scales. During the last decade, breakthroughs have been witnessed in the development of plasmonics, such as integrated photonic circuits [1–3], photovoltaics [4], and biosensing [5]. Recently, graphene plasmonics has attracted considerable attention, which has shown appealing properties: 1) Graphene plasmonics have extreme large mode confinement which has been verified by experiments [6–8]. 2) The Fermi level EF relative to the Dirac point, which is related to the optical response of graphene can be chemically or electrostatically tuned [9] in less than a nanosecond [10]. 3) Graphene surface plasmon waves (GSPW) could potentially provide longer propagation lengths compared to metallic surface plasmon waves (MSPW) [11, 12] in the infrared region. These unique properties enable graphene as a promising platform for infrared plasmonic applications. Localized plasmon mode has been investigated in nano-ribbons [8,13,14], nano-disks [15], and graphene-metal hybrid plasmonic antennas [16, 17]. An etched diffractive grating on silicon has been used to efficiently excite highly confined plasmonic waves in monolayer graphene [18, 19]. A Bragg reflector and defect microcavity have recently been studied in the graphene waveguide [20]. Transverse electric and magnetic surface mode in the terahertz regime have been theoretically investigated [21, 22].

A high-speed modulator with a small footprint and a large optical bandwidth is one of the key components in optical communication systems and on-chip optical interconnect, especially in wavelength-division multiplexing (WDM) systems. Recently, waveguide-type and free-space modulators implemented on graphene have been reported from the optical communication wavelength regime, to the mid-infrared and the terahertz (THz) regime [10, 12,13,20,23]. The operating principles for most of the graphene-based waveguide-type modulators (except one paper based on electrical modulation of the mode index and the phase of the MZI modulator with the footprint of 4×30 μm² [24]) and some of the free-space modulators are based on electro-absorption [10, 23, 25], which is mainly relied on the modulation of the interband or intraband absorption transition of graphene by actively tuning the Fermi level of graphene with gate-voltage. Other free-space graphene modulators are mainly realized by tuning the resonance wavelength of the cavity/antenna structures [16, 17, 26, 27]. The resonance structures can greatly enhance the interaction between light and matter to reduce the size of the devices. However, they can only operate in a narrow wavelength range or at a single wavelength, which are not desirable for photonic integrations, especially for WDM applications.

In this paper, we provide a different principle and method, the gate-voltage-controlled mode-guiding switching/mode-cutoff mechanism, to achieve the modulation/attenuation function. Different from the previous
studies, the proposed structure avoids patterning structures on graphene or substrate, thus diminishing the energy scattering on the edges. It also has the advantages of large modulation depth/attenuation range, wide bandwidth, and sub-micrometer chip-length with a nanoscale lateral section, which is promising for future graphene-based integrated photonic devices.

2. Gate-voltage tunable optical properties of graphene-based plasmonic waveguides

Electronic and optical characteristics of 2D graphene as functions of frequency, temperature, and carrier density have been analytically and experimentally studied widely [11, 16, 20]. They can be adjusted by varying the Fermi level, based on the fact that the carrier density of graphene can be changed by chemical doping or applied electrostatic field. The complex surface conductivity of graphene dominated by intraband and interband transitions is estimated within the random-phase approximation [28] as:

$$\sigma(\omega) = \frac{2ie^2k_BT}{\pi\hbar^2(\omega + i\tau)^{-1}} \ln \left[ 2\cosh \left( \frac{E_f}{2k_BT} \right) \right]$$

$$+ \frac{e^2}{4\hbar} \left\{ \frac{1}{2} + \frac{1}{\pi} \arctan \left( \frac{h\omega - 2E_f}{2k_BT} \right) \right\}$$

$$- \frac{i}{2\pi} \ln \left[ \frac{(h\omega + 2E_f)^2}{(h\omega - 2E_f)^2 + (2k_BT)^2} \right]$$

(1)

where $h$ is the reduced Planck’s constant, $\omega$ is the angular frequency, $\tau$ is the carrier relaxation time, $k_B$ is the Boltzmann constant, and $T$ is the temperature. The Fermi level $E_f$, which is proportional to the square root of gate voltage $V_g$, can be easily calculated according to Ref. [29]. In the following simulations, graphene is treated as an anisotropic material. The in-plane permittivity is approximated to be

$$\varepsilon = 1 + \frac{i\sigma}{\varepsilon_{\text{off}}aG}$$

(2)

where $a$ is the thickness of graphene which is estimated as 0.6 nm. The out of plane permittivity is 2.5, obtained based on the graphite dielectric constant.

Surface plasmon polariton (SPP) waves can be supported in a 1D slab waveguide constructed with a graphene sheet sandwiched between two dielectric mediums above and below. Under the condition free space wave vector $k_0 \ll k_{sp}$, the effective index of $N_{eff} = k_{sp}/k_0$ which is inversely proportional to the complex surface conductivity, can be calculated with Eq. (4) in Ref. [11]. It reveals that the effective index of the 1D SPP waveguide can also be adjusted by varying the Fermi level of graphene. Through applying different gate voltage patterns to a graphene sheet, propagation modes with low attenuation coefficients and radiation modes with high attenuation coefficients can be formed. This property can be used to build a modulator and a variable optical attenuator (VOA) of graphene, which is described in more details in the next section.

In the following, a model for a tunable 2D graphene-based plasmonic waveguide is built. As shown in Fig. 1, a monolayer graphene sheet is sandwiched between two aluminum oxide buffer layers (spacers) which have a low absorption in infrared wavelength range on a doped silicon substrate. This forms a 1D field confinement in the y-direction. Three separated gold-plated silicon gating pads are placed on top of the structure. The gating pads divide the waveguide into two different sections to provide another 1D field confinement along the x-direction, where the middle part is the core section and the others are the cladding sections. If the voltage applied to the cladding is higher than that to the core, the SPP waves will be confined within the core region, due to higher effective index of the core than the surrounding cladding layers along the x-direction. This guiding mechanism is similar to that of a dielectric channel waveguide, but only on the one-atom-thick scale. When a suitable gate voltage applied to the core section maintains the Fermi level at a constant value forming a fixed effective index of $N_{eff}$ (core), a different voltage applied to the cladding section will result in a low, equal, or high effective index of $N_{eff}$ (cladding). Thus tunable functions such as 2D mode guiding, 1D mode guiding, or mode cutoff can be achieved. Especially, by decreasing the voltage applied to the cladding, its Fermi level is lower than that of the core, thus the vast majority of energy will diffuse to the cladding, only very small fraction of energy remains in the core due to the change of the effective index in the cladding. The energy diffusing to the cladding will be eventually absorbed, and a high attenuation mode will appear. The change of the Fermi level is assumed to be sharp in two neighboring graphene sections. In fact, gaps are controlled at a very small value and the Fermi level will have a smooth transition between the core and the cladding.

Figure 1 Schematic of the tunable plasmonic graphene waveguide configuration. The height of each layer is $H_1 = H_2 = 50$ nm, $H_3 = 10$ nm. The width of the gating pads are $W_1 = W_2 = 650$ nm, $W_3 = 200$ nm and the length of the waveguide is $L = 500$ nm. The thickness of graphene is set to be $t_G = 0.6$ nm with the relaxation time of $\tau = 0.25$ ps, and the working temperature is $T = 300$ K. DC voltages are applied to the silicon gating pads to adjust the Fermi level. Here $V_1$ and $V_2$ stand for the voltages applied to the cladding and the core, respectively.
The finite-difference time-domain (FDTD) method with perfectly matched layer absorbing boundary conditions is used to evaluate the optical performance of the structure. The Fermi level in the core section is first set to be 0.6 eV, and that in the cladding section is 0.8 eV in the simulation. Figure 2 shows the light intensity profiles for frequencies at \( f = 35 \) THz and 40 THz, respectively. It is evident that the discontinuity in effective index in the \( x \)-axis can confine the SPP waves within the core section, forming a 2D guiding mode. A considerable part of the energy still distributes in the cladding section for \( f = 35 \) THz (Fig. 2a), while this proportion of the energy becomes much smaller for \( f = 40 \) THz (Fig. 2b). In the range of interest, the effective SPP index difference is approximately proportional to the frequency, leading to the confinement of SPP waves to become larger when the frequency increases. Defining the mode-field diameter \( W_{\text{MFD}} \) in the \( x \)-axis to be twice the \( e^{-2} \) radius of the optical power in the center and \( W_{\text{core}} \) as the width of the core, it gives \( W_{\text{MFD}}/W_{\text{core}} = 2.15, 1.36, \) and 1.04 for the \( f = 35, 40, \) and 45 THz, respectively.

Figure 3 shows the Fermi level patterns, the corresponding effective indices in the core and the cladding regions of the structure in the \( x \)-axis, and their normalized light intensity profiles in the \( x-z \) plane, respectively. Fermi level in the core is set to be 0.6 eV in all situations. As the effective index is inversely proportional to the square of Fermi level, one can see that for the situation of the Fermi level in the cladding higher than that in the core, the SPP waves are mainly confined in the core (Fig. 3a). Reducing Fermi level in the cladding can transform the propagation mode from tight confining state to weak confining state and increase \( W_{\text{MFD}} \). When Fermi level in the cladding is the same as that in the core, the SPP waves diffuse into the whole graphene plane very slowly within the distance of 500 nm (Fig. 3b). As the Fermi level in the cladding continues to decrease, it is evident that the propagation mode is cut-off and the radiation mode emerges. The effective index discontinuity “pulls” the energy from the core into the cladding and provides higher attenuation coefficient (Fig. 3c). The attenuation reaches the top level near the Fermi level of \( E_f = 0.2 \) eV when the SPP waves start to assemble at the boundary of the core section (Fig. 3d). Further reducing the Fermi level in the cladding can result in more energy concentrating at the boundary, and the attenuation falls a little bit (Fig. 3e). This kind of mode is similar with the edge mode at the boundary between the regions where the imaginary parts of the conductivities \( \sigma_{g,i} \) have different signs [30]. However, it is noted that here \( \sigma_{g,i} > 0 \) is kept in the whole graphene strip, and thus, it is a kind of quasi-edge-mode.

The effect of the core width on the attenuation of the waveguide was investigated in two typical states of \( E_{\text{cladding}} = 0.2 \) eV and \( E_{\text{cladding}} = 0.8 \) eV, and is shown in Fig. 4a. When the core width increases from 200 nm to 280 nm, the attenuation for \( E_{\text{cladding}} = 0.8 \) eV is nearly constant, from 3.80 dB/\( \mu \)m to 3.96 dB/\( \mu \)m, while the attenuation for \( E_{\text{cladding}} = 0.2 \) eV decreases linearly, from 25.40 dB/\( \mu \)m to 20.54 dB/\( \mu \)m. It means that a wide core results in slightly small leakage of the energy from the core into the cladding at a given short propagation distance, for \( E_{\text{cladding}} = 0.2 \) eV. When the structure is applied to achieve the attenuation function, it can be concluded that narrowing the core may increase the attenuation. However, the effect is limited by approximate 0.6 dB/\( \mu \)m increment per 10 nm. In other words, such low increment means high tolerance on the core width. The attenuation performance will not be much affected even if the deviation of the core width is over 30 nm.

Wavguides and their components used in integrated photonic circuits prefer wide optical bandwidth in operations. Different Fermi levels applied to the cladding section have also been considered. The structure we propose was studied in the 35–50 THz range. Figure 4b shows the attenuations of the waveguide for \( E_{\text{cladding}} = 0.15, 0.2, 0.4, 0.6, 0.8 \) eV, respectively. It can be seen that the attenuations stay low in the propagation state (\( E_{\text{cladding}} = 0.8 \) eV) and low attenuation state (\( E_{\text{cladding}} = 0.6 \) eV), while having large difference in the high attenuation states (\( E_{\text{cladding}} = 0.15, 0.2, 0.4 \) eV). In addition, the frequency at the peak of the attenuation becomes higher as the \( E_{\text{cladding}} \) increases. Higher attenuation range can be achieved by shifting to higher working frequency. Note that the attenuation at 45.5 THz is...
Figure 3 The Fermi level patterns, corresponding effective indices and light intensity propagation profiles of the waveguide under different $E_f$-values: (a) $E_{f,\text{cladding}} = 0.8$ eV, (b) $E_{f,\text{cladding}} = 0.6$ eV, (c) $E_{f,\text{cladding}} = 0.4$ eV, (d) $E_{f,\text{cladding}} = 0.2$ eV, (e) $E_{f,\text{cladding}} = 0.15$ eV. The working frequency is fixed at $f = 37$ THz.
up to 51.2 dB/μm at the $E_{\text{cladding}} = 0.2$ eV state. From the attenuation characteristics, more than 15 THz bandwidth can be achieved, showing great potential as a modulator or an attenuator.

3. Nano graphene-based modulator and VOA waveguides

Obviously, the dependence of the attenuation of the waveguide on the Fermi level of the cladding can be easily employed to achieve functions of modulators and variable optical attenuators. For a more clear description of the controllable properties of the waveguide structure, the attenuation of the structure as the function of the Fermi level of the cladding is shown in Fig. 5. As can be seen, the attenuation remains at a relative low level in the propagation mode ($E_{\text{cladding}} = 0.8$ and 0.7 eV), and this condition will not change significantly even at the diffusing state ($E_{\text{cladding}} = 0.6$ eV) within a very short propagation distance at the beginning. Further decreasing $E_{\text{cladding}}$ will lead to the rapid increment of the attenuation. The attenuation reaches the top when $E_{\text{cladding}} = 0.25$ eV, and drops back slightly when $E_{\text{cladding}} = 0.2$, 0.15 eV, because the quasi-edge-modes emerge, shown in Fig. 3d and e.

To build a modulator, two typical states with $E_{\text{cladding}} = 0.8$ and 0.2 eV are selected as the on and off states, respectively. In the on-state of $E_{\text{cladding}} = 0.8$ eV, the overall throughput 63.4% of the structure is detected and the modulator works in a low attenuation state with $\alpha_{\text{on}} = 4.0$ dB/μm, for the working frequency of 37 THz. Conversely in the off-state of $E_{\text{cladding}} = 0.2$ eV, the throughput is only 5.36% in this structure and the modulator works in a high attenuation state with $\alpha_{\text{off}} = 25.4$ dB/μm. As a result, 21.5 dB/μm modulation depths can be achieved, and 3-dB modulation depth can be satisfied for the modulator length as short as 139.8 nm.

In addition, the waveguide shown in Fig. 1 can also be employed as a variable optical attenuator directly, by continuous tuning the Fermi level in the cladding. As shown in Fig. 5, the attenuation of the waveguide can increase continuously from 4.0 dB/μm to 26.2 dB/μm by changing the Fermi level in the cladding from 0.8 eV to 0.25 eV, at frequency of 37 THz. The attenuation range is 22.2 dB/μm. Again, higher attenuation range can be achieved by shifting to higher working frequency. As the high tolerance on the core width, the performance will not be significantly affected even if the deviation of the core width is as high as 30 nm.

4. Conclusion

To summarize, we have proposed nanoscale tunable graphene-based plasmonic waveguides in the mid-infrared
and/or THz frequency regimes and investigated their performances in details. Based on the gate-voltage controllable characteristics of graphene, different Fermi energy level patterns by exerting bias voltages can be used to realize the propagation or the attenuation function on a single 2D graphene strip. Within the scope of our investigation, different modes with low or high attenuations have been observed, and wide dynamically attenuation control has been achieved. Moreover, this structure has high tolerance on the core width, and can be operated in a wide bandwidth. Two applications of the graphene-supported plasmonic waveguide, the modulator and the variable optical attenuator, have been presented. This waveguide structure can be used as the fundamental component for optical communication interconnect in ultrahighly integrated photonic circuit, especially for high-performance mid-infrared modulators where a viable way towards realizing such devices remains elusive.

Acknowledgments. This work was supported by Guangdong Province High-Tech Zone Development Program (No. 2012B010900022), Science and Technology Projects of Education Department of Guangdong Province (2012KJCX0038), and A*STAR SERC grant (Grant No.: 112 280 4038).

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