Tunable magnetoplasmons for efficient terahertz modulator and isolator by gated monolayer graphene

Yixuan Zhou, Xinlong Xu,* Haiming Fan, Zhaoyu Ren,* Jintao Bai and Li Wang

This work demonstrates a pathway for efficient terahertz modulator and isolator based on the tunable magnetoplasmons in graphene.

Please check this proof carefully. Our staff will not read it in detail after you have returned it. Translation errors between word-processor files and typesetting systems can occur so the whole proof needs to be read. Please pay particular attention to: tabulated material; equations; numerical data; figures and graphics; and references. If you have not already indicated the corresponding author(s) please mark their name(s) with an asterisk. Please e-mail a list of corrections or the PDF with electronic notes attached – do not change the text within the PDF file or send a revised manuscript.

Please bear in mind that minor layout improvements, e.g. in line breaking, table widths and graphic placement, are routinely applied to the final version.

Please note that, in the typefaces we use, an italic vee looks like this: v, and a Greek nu looks like this: ν.

We will publish articles on the web as soon as possible after receiving your corrections; no late corrections will be made.

Please return your final corrections, where possible within 48 hours of receipt, by e-mail to: pccp@rsc.org.

Reprints—Electronic (PDF) reprints will be provided free of charge to the corresponding author. Enquiries about purchasing paper reprints should be addressed via: http://www.rsc.org/publishing/journals/guidelines/paperreprints/. Costs for reprints are below:

<table>
<thead>
<tr>
<th>No of pages</th>
<th>Cost (per 50 copies)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First</td>
</tr>
<tr>
<td>2-4</td>
<td>£225</td>
</tr>
<tr>
<td>5-8</td>
<td>£350</td>
</tr>
<tr>
<td>9-20</td>
<td>£675</td>
</tr>
<tr>
<td>21-40</td>
<td>£1250</td>
</tr>
<tr>
<td>&gt;40</td>
<td>£1850</td>
</tr>
</tbody>
</table>

Cost for including cover of journal issue:
£55 per 50 copies

Queries are marked on your proof like this Q1, Q2, etc. and for your convenience line numbers are indicated like this 5, 10, 15, ...
<table>
<thead>
<tr>
<th>Query reference</th>
<th>Query</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>Please carefully check the spelling of all author names. This is important for the correct indexing and future citation of your article. No late corrections can be made.</td>
<td></td>
</tr>
</tbody>
</table>
Tunable magnetoplasmons for efficient terahertz modulator and isolator by gated monolayer graphene †

Yixuan Zhou, Xinlong Xu, Haiming Fan, Zhaoyu Ren, Jintao Bai and Li Wang

Terahertz (THz) technology has been a promising tool for sensing, spectroscopy, imaging, and communication. However, only few devices have shown efficient performance for future THz technology. Herein, we propose a device based on tunable magnetoplasmons in gated monolayer graphene for THz wave modulation and isolation. The relative transmission and the Faraday rotation angle of the device have been calculated by combining the Fresnel method with the voltage-dependent Drude model. Our results suggest that a superior modulation depth and giant Faraday rotation due to the cyclotron effect in the classical regime by intraband transitions in graphene offer an effective, uniform, and flexible tunability for THz wave. And the modulating and isolating manipulations by graphene can range from 0 to 2 THz, with electron–hole asymmetry originating from variable scattering rate of magnetoplasmons. Moreover, the thickness effect of the thin substrate is also studied for better performance of the device, taking advantage of the unavoidable Fabry–Perot (F–P) effect. This work demonstrates a pathway for efficient THz modulator and isolator based on the magneto-optical polarization effect in graphene.

1. Introduction

As the most unexplored electromagnetic spectrum, terahertz (THz) wave has wide applications for biological imaging, time-domain spectroscopy, high sensitive sensing, and high-speed communications. It has bridged the gap between microwave region with efficient electronic devices and infrared-visible region with efficient photonic devices.1–3 However, only few efficient devices can be used for THz wave modulated and isolated manipulation so far. Graphene, a two-dimensional honeycomb lattice with the sp² hybridized carbon atom arrangements having extraordinary carrier properties4 and optoelectronic applications5 shows several novel features for potential device applications in the THz region.6–9 For example, unlike the interband transitions10 with a constant absorption coefficient for each layer in infrared-visible region, the intraband transitions dominate the THz region and result in a THz conductivity well described by the Drude model.8,9,11,12 Furthermore, by virtue of the ambipolar electric field effect in graphene the electrons and holes can be tuned up continuously in concentration as high as 10¹³ cm⁻²,4 which in turn opens a new way for tunable THz photoelectric devices7–9 with a long lifetime of graphene plasmon.

The magnetoplasmons in graphene also show the same noteworthy effects as the plasmons in the THz region. This effect is relatively less studied and reported in literature,13–17 thus letting alone the tunable THz magneto-optical devices. Crassee et al.18,19 suggested that magnetoplasmons in monolayer graphene on SiC induce a giant Faraday rotation in modest magnetic fields perpendicular to the graphene basal plane. Yan et al.20 investigated the edge and bulk plasmon modes in patterned graphene disks and suggested a potential THz application with graphene. A recent review paper by Grigorenko et al.21 also suggested exciting applications with graphene plasmonics. More interesting devices with graphene would be a modulator and isolator with both electric and magnetic effects.
tunability. To our best knowledge, this voltage-dependent magneto-optic application has not been studied yet, while these can be achieved with the advantage of novel electron and hole properties in graphene.

In the presence of the magnetic field, the carrier states can be divided into a classic and quantum regime. In a quantum regime under a high magnetic field, the sample is weakly doped, which can be regarded as 2D electron gases. The Quantum Hall effect will rise when the Fermi level crosses different Landau levels (LLs). In a classic regime under a low magnetic field, the carrier density is high and the Drude theory can be used to describe the dynamics of carriers in the THz region. Due to the pronounced ambipolar electric field effect in graphene, these two regimes are controllable, while the potential THz magnetoplasmons in a strong doped classic regime can gain more interest for novel device applications.

In this paper, we propose a tunable magnetoplasmons in a classic regime based on gated monolayer graphene for efficient THz modulator and isolator. We calculated the relative transmission and the Faraday rotation angle based on the Fresnel method combined with the voltage-dependent Drude model. Our results suggest that the manipulation can range from 0 to 2 THz with electron–hole asymmetry. The modulation depth can approach 8.8% with magnetic tunability and 13.7% with electric tunability. The Faraday rotation angle can attain a value of 3.8° originating from the cyclotron effect by intraband transitions in graphene. These offer an effective, uniform, and flexible tunability in the THz region. In addition, we studied the thickness dependence of the thin substrate for better performance in making full use of the Fabry–Perot (F–P) effect in the device.

2. Method

2.1 Graphene/spacer/substrate model

Fig. 1 demonstrates the device with a multi-layer structure consisting of graphene, spacer layer, and substrate with the magnetic field $B$ perpendicular to the graphene basal plane. The complex refractive indexes of air, spacer layer, and substrate are $n_i$, $n_s$, and $n_d$. The thicknesses of the spacer layer and substrate are $d_3$ and $d_4$, respectively. The top and back metal electrodes can be used to tune the carrier density. We study the transmission of the device using the Fresnel method treating the graphene layer as an optical zero-thickness film.

The Fresnel coefficients $t_{ij} = 2n_i/(n_i + n_j)$ and $r_{ij} = (n_i - n_j)/(n_i + n_j)$ are used to describe the transmission and reflection on the interface between optically thick medium, where $n_{ij} = n_{ij} + k_{ij}$ is the complex refractive index. The transmission through the interface of air/graphene/spacer is given by:

$$t_{gras} = 2n_1/[n_1 + n_3 + Z_0 \sigma_Z],$$

and the internal reflection from the graphene–spacer interface can be expressed as:

$$r_{gras} = [n_3 - n_1 - Z_0 \sigma_Z]/[n_3 + n_1 + Z_0 \sigma_Z],$$

where $Z_0 \approx 377$ is the vacuum impedance. The THz conductivity of graphene for left (+) and right (−) circularly polarized wave has the form:

$$\sigma_{\pm} = \sigma_{\pm}^n \pm i\sigma_{\pm}^r,$$

where $\sigma_{\pm}^n$ and $\sigma_{\pm}^r$ are the real part of the diagonal conductivity and the Hall conductivity, while $\sigma_{\pm}^n$ and $\sigma_{\pm}^r$ are the imaginary parts.

We assume that the incident THz wave is linearly polarized as shown in Fig. 1, and the electric fields change from +1 to −1 after transmitting through the graphene and spacer layer. With all F–P interference considered in spacer layer, the transmission coefficient can be expressed as:

$$t_{in} = \frac{E_{in+}(\omega, B)}{E_{0}(\omega, B)} \frac{t_{34}p_{spc}(\omega, d_3)p_{air}(\omega, -d_3)}{1 - r_{gras}r_{34}p_{spc}^{-1}(\omega, d_3)}$$

where $\omega$ is the angular frequency, $p_{air}(\omega, L) = \exp(i\omega n_d L/c)$ and $p_{spc}(\omega, L) = \exp(i\omega n_s L/c)$ are transmission factors in the air and spacer layer. Then multiple reflected rays in the substrate superpose coherently and the transmitted electric fields out of the device tune into $E_{ot\pm}$, with the transmission amplitudes following the form:

$$t_{ot\pm} = \frac{E_{ot\pm}(\omega, B)}{E_{0}(\omega, B)p_{air}(\omega, d_3 + d_4)}$$

$$= t_{in\pm} \times \frac{t_{41}p_{sub}(\omega, d_4)p_{air}(\omega, -d_4)}{1 - r_{43}r_{41}p_{sub}^{-1}(\omega, d_4)}$$

where $p_{sub}(\omega, L) = \exp(i\omega n_d L/c)$ is the transmission factor of the substrate. And the transmittance can be written separately as:

$$T_{in} = \frac{n_t}{2} \times (|t_{in+}|^2 + |t_{in-}|^2)$$

$$T_{ot} = \frac{(t_{ot+}|^2 + |t_{ot-}|^2)}{2}$$

![Fig. 1 Schematic of transmission of the THz wave through a graphene/spacer/substrate structure.](image-url)
And the Faraday rotation angle is given by:

\[
\theta_F = \frac{\arg(t_{in}) - \arg(t_{out})}{2} = \frac{1}{2} \tan^{-1} \left( \frac{\text{Im}(t_{in}/t_{out})}{\text{Re}(t_{in}/t_{out})} \right)
\]  

where \( t_{in} = t_{out} \) means the substrate material should not introduce Faraday rotation itself.

The transmission of the same THz wave through the spacer layer and the substrate without graphene can be calculated in a similar way. We define \( T_{in} \) and \( T_{out} \) as the transmittance of the rays passing through the bare spacer layer and the substrate (without graphene), respectively. And the relative transmission of graphene as \( T/T' = T_{in}/T_{in}' = T_{out}/T_{out}' \). Although we have used the above mentioned equations for our calculation, the simple expressions for the relative transmission and Faraday rotation angle of graphene turns out to be helpful in understanding the resonant peaks of magnetoplasmons and the substrates selection.

2.2 Spacer layer and substrate selection

We assume a transparent substrate in the THz region (such as SiO\(_2\), high-resistance Si) and keep only the linear terms in conductivity, the extinction in the transmission \( T \) and the Faraday rotation angle \( \theta_F \) of graphene can be simplified as:

\[
1 - T/T' \approx 2\beta(\omega)Z_0\sigma_{xx}(\omega, B)
\]

\[
\theta_F(\omega, B) \approx \beta(\omega)Z_0\sigma'_{xy}(\omega, B)
\]

where \( \beta(\omega) \) is a function specific to the spacer layer and the substrate:

\[
\beta(\omega) = \frac{1}{n_3 + 1} + \frac{2n_4}{n_3^2 - 1} + \frac{M^2}{1 - M^2}
\]

\[
M = \frac{(n_2 - 1)(n_3 - n_4)}{(n_3 + 1)(n_3 + n_4)} \exp \left( -\frac{2\omega d_3 \kappa}{\epsilon} \right)
\]

It depends on the refractive index of the spacer layer \( n_3 \), substrate \( n_4 \), the extinction coefficient \( \kappa_3 \), and the thickness of spacer layer \( d_3 \). It is noticed that eqn (7) can be simplified into a similar two-layer form as reported by Crassee et al.\(^{18}\). Proper substrate selection would be very important to optimize the Faraday rotation angle \( \theta_F \) and \( 1 - T/T' \) from (5) and (6). This condition mainly comes from the influence of \( \beta(\omega) \) with a larger value for better performance. For better electrical tuning performance, the spacer layer is typically a thin insulator. The calculated results prove that small \( n_3 \) is a very important factor (as described in S1 in the ESI\(^{\dagger}\)). As a good selection, SiO\(_2\)-Si substrate has a large value of \( \beta(\omega) \), and is suitable for modern technology. Thus it is chosen as the substrates in our following simulation work.

The F-P interference has a different influence on different thicknesses of spacer layer and substrate. In this work, a typical value of 300 nm is used for the space layer, which will avoid fluctuation of transmission but introduce approximately 30% loss of the incident THz wave due to F-P effect (as shown in Fig. S2(a) in the ESI\(^{\dagger}\)). For better performance, a suitable thickness of Si substrate should be used for different applications in certain THz frequencies (as shown in Fig. S2(b) in the ESI\(^{\dagger}\)).\(^{2,24}\)

It can be noticed that the substrate thickness will not affect the values of \( 1 - T/T' \) and \( \theta_F \) in our results, because the F-P effect can be reduced and Si is assumed as a transparent layer in the THz region.

2.3 Tunable voltage-dependent Drude conductivity in graphene

Monolayer graphene shows the THz Drude conductivity as following:\(^{9,11,14,23,26}\) \( \sigma(\omega) = i\omega\varepsilon_0\varepsilon_0' + i\omega\varepsilon_0\varepsilon_0'' \), where \( \varepsilon_0 \) is the polarization rate. The Drude weight \( D \) has the form \( D = e^2|E_F|/\hbar^2 \), where \( e > 0 \) is the elementary charge and \( E_F \) the Fermi energy. In a classic regime the Dirac quasiparticles in graphene are expected to exhibit the classical cyclotron resonance effect. The diagonal and off-diagonal conductivity components can be expressed as:\(^{13,18}\)

\[
\sigma_{xx}(\omega, B) = \frac{D}{\pi} \times \frac{(\omega - \omega_c)^2 - (\omega + i\Gamma)^2}{\omega_c^2 - (\omega + i\Gamma)^2}
\]

\[
\sigma_{xy}(\omega, B) = -\frac{D}{\pi} \times \omega_c - (\omega + i\Gamma)^2
\]

where \( \omega_c \) is the cyclotron frequency and agrees well with the relation \( \omega_c = eBv_F^2/\hbar^2 \) with the Fermi velocity \( v_F = 1.1 \times 10^6 \) m s\(^{-1}\), Fermi energy is related to the carrier density by \( E_F = \pm h\nu_F(\pi|n|)^{1/2} \) with negative (positive) corresponding to hole (electron) doping. The carrier density \( n \) is related to the quality of the graphene, preparation methods, substrate materials, as well as the gate voltage. The first three factors influence the initial carrier concentration, which determine the charge neutral point (CNP) of different devices. The last one allows us to tune the Fermi level \( E_F \). In the following calculation, we assume the carrier density in graphene is related to the gate voltage \( V_g \) by \( n = 7.5 \times 10^{10} \times |V_g - V_{CNP}| \) cm\(^{-2}\) V\(^{-1}\), where \( V_{CNP} \) defines the CNP of the sample.\(^{11,30}\) The scattering rate value \( \Gamma \) would not be constant under a different voltage.\(^{31,32}\) We take the \( \Gamma \) as equal to 115 cm\(^{-1}\) (14.3 meV) at hole concentrations, and increasing linearly with the carrier concentration to 195 cm\(^{-1}\) (24.2 meV) at \( V_g - V_{CNP} = 60 \) V for electron doping, which is approximate to the experimental data by Horng et al.\(^{11}\).

The experimental values of the Drude weight that arise from free-carrier intraband transitions are always found to be lower than the theoretical prediction\(^{11,18,33}\) based on the Boltzmann transport theory, which is due to the corresponding changes in interband transitions.\(^{33}\) This effect is ignored in our simulation, which may causes slight reduction in the final value of the Faraday rotation angle.

3. Results and discussion

3.1 Tunable magnetoplasmons of gated monolayer graphene

Fig. 2(a) and (b) show the calculated extinction ratio \( 1 - T/T' \) of gated monolayer graphene in magnetic fields up to 7 T, with a gate voltage \( V_g - V_{CNP} \) at \(-10\) V and \(-80\) V. Fig. 2(a) indicates that the Drude plasmon response can be tuned to magnetoplasmons under the magnetic field with a series of strong...
resonant magnetoplasmon peaks, which shift from 0 to 12.4 THz broadly with the increase of the magnetic field. The magnetic dependent modulation depth defined as $\frac{T_0}{T}$, can be maximum 8.8% at the low THz region below 2 THz. Fig. 2(b) shows that with an increase of the density of carriers, the magnetoplasmon peaks shifts from 0 to 4.2 THz. The magnetic dependent modulation depth approaches a maximum of 14.4% in the low THz region. When $B$ is 0 T, the maximum voltage dependent intensity modulation depth defined as $\frac{T_0(V_{g} - V_{\text{CNP}})}{T_0(10 \text{ V})} = 15.7\%$. This is inherently a broadband region as compared with metamaterial modulator$^{34}$ and is similar to the result by Sensale-Rodriguez et al.$^{9}$ The Faraday rotation angle $\gamma$ in magnetic fields up to 7 T (shown in Fig. 2(c) and (d)) with a gate voltage $V_{g} - V_{\text{CNP}}$ at −10 V and −80 V, respectively gives rise to positive rotations at low frequency and negative rotations at high frequency. The positions of the maximum absolute slope $d\theta_{F}/do$ coincides with the magnetoplasmon peaks in Fig. 2(a) and (b). From Fig. 2(c), the maximum Faraday rotation angle exceeds 1.4° under a modest magnetic field. It is worth noticing here that under the spectral region of 0 to 2 THz, for a normal THz time-domain spectroscopy system,$^{35}$ the Faraday rotation angle is quite uniform. It means we can achieve a broadband and uniform isolator for the THz system. Fig. 2(d) shows a remarkable maximum Faraday rotation angle exceeds 3.8° when $B$ lies between 6 and 7 T, which is a giant value compared with the doped silicon,$^{36}$ considering just a single layer of graphene.

To gain further insight into the different response of electron and hole, the gate voltage dependent mapping of the extinction ratio at a magnetic field $B$ = 7 T is shown in Fig. 3(a). The gate voltage, where negative (positive) corresponds to hole (electron) doping, has a range from −80 to 60 V, and corresponds to a modulation range of the Fermi energy from −0.32 to 0.27 eV. The dashed line in Fig. 3(a) shows that the magnetoplasmon peak position is approximate electron and hole symmetry with the applied voltage, while the intensity of hole and electron response is quite electron–hole asymmetry. This could be due to a different response of electron and hole under the same applied voltage with different effective mass and scattering parameters. The magnetic field and gate voltage dependent absolute value of the magnetoplasmon frequency is presented in Fig. 3(b). The magnetoplasmon peak positions in Fig. 3(a) (dash line) obviously follow the locus of $|\omega_c|$, which can be used to predict their positions and variation tendencies. In the high doped region, the magnetoplasmon frequency shifts from 0 THz to around 5 THz with magnetic field from 0 to 7 T. Combining the linear correlation between the magnetoplasmon frequency and the magnetic field, this effect introduces an absorption decrease below 2 THz when the magnetic field becomes strong. On the other hand, $|\omega_c|$ has a gate voltage dependent variation with $|\omega_c|^{-1}$ and $|V_{g} - V_{\text{CNP}}|^{-1/2}$, and the magnetoplasmon peaks move to a high frequency in the low doped region, which introduces the decrease of absorption with the gate voltage.

The electron–hole asymmetry, in particular, is obvious in Faraday rotation angle spectroscopy (Fig. 4) and gives rise to a

---

**Fig. 2** (a, b) The extinction ratio $1 - T/T'$ in magnetic fields up to 7 T of graphene with a gate voltage $V_{g} - V_{\text{CNP}}$ at −10 and −80 V, respectively. (c, d) The Faraday rotation angle $\theta_F$ in the 7 T magnetic fields of graphene with gate voltage −10 and −80 V.
positive rotation at a lower frequency and negative rotation at a higher frequency for holes, while this becomes opposite for electrons. For the same carrier density, the holes will show a higher Faraday rotation angle as compared with electrons. It is also noticed that the Faraday rotation angle in the electron regime tends to saturation when the voltage reaches 40 and 60 V, both of which have a similar $\theta_F$ in the low frequency region. This could be due to the increase in the scattering rate with the carrier density in the electron regime, which also reflects that $\Gamma$ is another important factor for the Faraday angle value. For example, in our calculation we obtain the maximum Faraday rotation angle of 3.8° with the scattering rate equal to 14.3 meV. If we set $\Gamma = 10$ meV with the other conditions remaining, a Faraday rotation angle of 4.8° can be obtained with an increase of 21%.

### 3.2 Graphene THz modulator and isolator

Related to the above studies, special attention is taken in the region 0–2 THz, where most applications of THz technology are located. In this region uniform responses are observed both for the extinction ratio and the Faraday rotation angle in Fig. 2. The broad-band, superior intensity modulation depth and the giant Faraday rotation angle reveal good potential with the gated monolayer graphene for efficient THz modulator and isolator. 1 THz is chosen as a representative and Fig. 5(a) illustrates the gate voltage dependent $1 - T/T'_{0}$ of gated graphene in magnetic fields up to 7 T. The maximum extinction ratio 0.224 occurs in the heaviest doping region with zero magnetic fields, reducing with decreasing the carrier density to a minimum 0.089. When the magnetic field increases to 7 T, a reduction is observed with maximum 0.113 in the high carrier region and minimum 0.008 in the low carrier region. The relative transmission change is approximately uniform with the tuning of both the magnetic and the electric. It roughly stabilizes at an intensity modulation depth of about 12% with magnetic tunability (0–7 T) and 15% with electric tunability (–10–80 V). This also implies that in any settled magnetic field, the transmission will be effectively controlled by electric tuning. These results prove that a combined effect of magnetic and electric tuning will introduce more flexibility, and reveal a pathway of gated graphene for THz intensity modulators.

Fig. 5(b) shows the gate voltage and magnetic field dependent mapping of the Faraday rotation angle of graphene at 1 THz in a hole regime. The Faraday rotation angle can be analyzed from two aspects. Firstly, the effect of the magnetic field $B$ in a certain settled doping regime is discussed. As shown in the top panel of Fig. 5(b), with $V_g - V_{CNP}$ at $–10$, $–40$ and $–80$ V, maximum values appear at the magnetic field equal to 2.27 T, 4.63 T and 6.65 T, corresponding to the increasing $\theta_F$ of 1.4, 2.7 and 3.8°. These peaks shift to a stronger magnetic field along with enhancement of the doping degree. Its locus is marked as a dotted line in the bottom panel of Fig 5(b). It implies that at a certain doping degree, the maximum of the Faraday rotation angle is intrinsic at a certain magnetic field intensity. This conclusion is important in the design of a graphene THz isolator and we explicitly give this relation in Fig. S4 in the ESL†. On the other hand, the gate voltage dependent change of $\theta_F$ at a settled magnetic field is also
discussed. In the region below 2 T, $\theta_F$ is roughly a constant for different doping levels and rises with $B$ to approach 2°. In the region up to approximately 5 T, an unbalanced increase with carrier density is shown, with more faster growing in the high carrier density region. Subsequently, the magnetic field dependent change of the Faraday rotation angle becomes very small when $B$ exceeds 5 T, and the maximum value has a distinction value lower than 0.17°. So for an appropriate value and effective electric tuning, we should choose a magnetic field below 5 T in the high doping range. Combining these two aspects, we should raise the carrier density but at a suitable magnetic field for a maximum or an appropriate Faraday rotation angle in the THz region. In addition, the maximum modulation voltage we used here is −80 V, corresponding to a hole concentration of $6 \times 10^{12}$ cm$^{-2}$. If we increase the density to $10^{13}$ cm$^{-2}$, a maximum angle of 4.9° is obtained. This is by 1.1° larger than the maximum angle of 3.8° as discussed above. Combined with the effect of $\Gamma$ mentioned before, this suggests that high-quality graphene samples with a lower scattering rate will improve more in the Faraday rotation angle and will result in a much better isolator performance.

If the thickness of the substrate is more than THz wavelength, the F–P effect from the substrate can be removed by windowing the THz waves. If the thickness of the substrate is comparable to the THz wavelength, the F–P interference will not be avoided absolutely. However, we found that proper selections of the thicknesses will become an effective solution for a better transmittance performance of both the modulator and isolator (as shown in Table S2 and Fig. S3 in the ESL†). For example, 0.225, 0.3, and 0.67 THz are some of the THz atmospheric windows. Appropriate choices of the substrate thickness can achieve multi-band useful devices working in these THz atmospheric windows. A thickness of 195 µm will work well in 0.225 and 0.67 THz and a thickness of 585 µm can be used efficiently at 0.225, 0.3, and 0.67 THz as shown in Fig. S3(b) in the ESL†.

4. Conclusions
In this work, we present a graphene device based on tunable magnetoplasmons. Our results suggest that gated graphene on top of SiO$_2$–Si can have a uniform broadband modulation with a superior modulation depth. The combined effect of magnetic and electric tuning will introduce more flexible tuning effect. It can have a giant Faraday rotation originating from the cyclotron effect in the classical regime by intraband transitions in graphene with a high carrier density but low magnetic fields. We also propose that it is necessary to make thicknesses selection of the thin substrates for better exploiting the unavoidable F–P interference of the device for THz applications. Our calculations and results suggest a promising pathway for an efficient THz modulator and isolator device based on the magneto-optical polarization effect in graphene.

Acknowledgements
This work was supported by the National Natural Science Foundation of China (No. 61275105, 10974152, 10834015, 21006079, 61077082), the Natural Science Basic Research Plan in the Shaanxi Province of China (No. 2012JXX-27), the PhD Programs Foundation of the Ministry of Education of China (No. 20106101110017), and the Northwest University Cross-discipline Fund for Postgraduate Students (10YJC11). Dr Xu acknowledges support from the Open Foundation of State Key Lab Incubation Base of Photoelectric Technology and Functional Materials (No. ZS12018).
References

1 B. Ferguson and X. C. Zhang, Nat. Mater., 2002, 1, 26–33.
7 A. Vakil and N. Engheta, Science, 2011, 332, 1291–1294.
17 V. P. Gusynin, S. G. Sharapov and J. P. Carbotte, J. Phys.: Condens. Matter, 2007, 19, 026222.
21 A. N. Grigorenko, M. Polini and K. S. Novoselov, Nat. Photonics, 2012, 6, 749–758.