Supplementary information for:

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

Yixuan Zhou[1], Xinlong Xu[1,2,a)], Haiming Fan[1], Zhaoyu Ren[1,b)], Jintao Bai[1], and Li Wang[2]

[1] *Nanobiophotonic Center, State Key Lab Incubation Base of Photoelectric Technology and Functional Materials, National Photoelectric Technology, Functional Materials and Application of Science and Technology International Cooperation Center, and Institute of Photonics & Photon-Technology, Northwest University, Xi'an 710069, China*

[2] *Beijing National Laboratory for Condensed Matter Physics, and Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*

S1 Space layer and substrate materials

We select weak absorption materials in THz region as a space layer, a simplified form of equation (7) (shown in the main text) can be written as: $\beta_{no-abs} \approx (n_3^2 + n_4^2 + 2n_4)/[2(n_3^2 + n_4)(n_4 + 1)]$. Fig. S1(a) show the refractive index n_3 and n_4 mapping of β under a weak absorption assumption. It is suggested that for better performance of devices, space layer should have a small β value as shown in the top panel in Fig. S1(a) and have low refractive index contrast (n_3 / n_4). For the case of high absorption of space layer, multiple reflections can be ignored and $\beta_{abs} \approx 1/(n_2 + 1)$. Define $\Delta\beta = \beta_{no-abs} - \beta_{abs}$, where $\Delta\beta$ represents the maximum decline of β originate from the absorption of space layer, which is expected as low as possible. There are two aspects to avoid high $\Delta\beta$: Select space layer with small n_3 and choose a suitable substrate with $n_3 \approx n_4$ (as shown in Fig. S1(b)). In this work, gated voltage is introduced in our model, and

a) Author to whom correspondence should be addressed. Electronic mail: xlxuphy@nwu.edu.cn.
b) Author to whom correspondence should be addressed. Electronic mail: rzy@nwu.edu.cn.

the spacer layer is thus typically insulator. Small value of n_3 becomes the most important influencing factor.

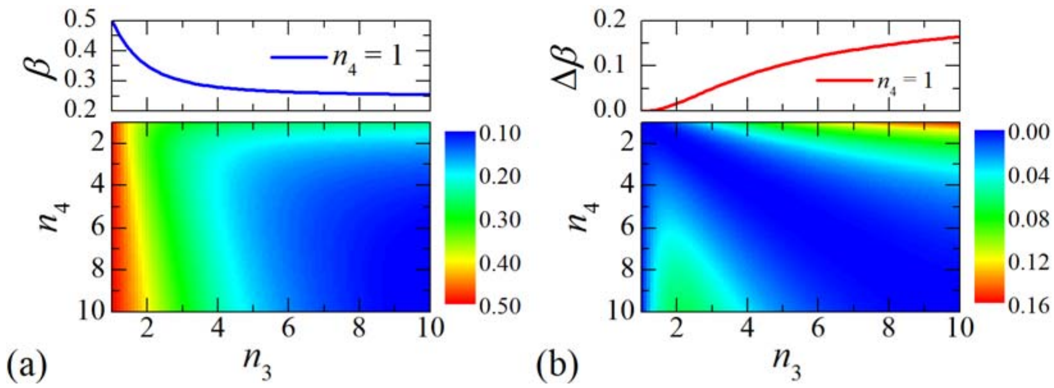

Fig. S1 (a) Bottom: Refractive indexes of space layer and substrate dependent mapping of β, for weak absorption of two layer substrates; Top: For one layer substrate condition. (b) Bottom: Refractive indexes of space layer and substrate dependent mapping of $\Delta\beta$; Top: For one layer substrate condition

Table S1 summarizes the materials for the substrate and space layer selection with 'Air' meaning free-standing. As a good selection, SiO_2/Si substrate has a large value of β. What's more important is that it has a good performance for applying voltage and is suitable for modern technology.

Table S1 Different material parameter dependence of β

Space layer		Substrate		β
Material	n_3	Material	n_4	
Air	1	Air	1	0.5
SiO_2	1.46	Air	1	0.4097
Si	3.42	Air	1	0.2894
SiC[a]	–	Air	1	0.3
SiO_2	1.46	Si	3.42	0.4211
Si	3.42	SiO_2	1.46	0.2587

[a]From Nat. Phys. **7,** 48-51 (2010).

S2 Fabry-Perot (F-P) interference of SiO_2/Si substrate for thickness selection

Fig. S2(a) shows the SiO_2 thickness dependent mapping of THz wave transmittance (T'_{in})

for bare SiO_2/Si substrate. Here, F-P interference introduced by the SiO_2 spacer layer has been taken into account. When the layer of SiO_2 is 300 nm in thickness, the transmittance has a constant value at about 0.7 in the broad band region as shown in the top panel of Fig. S2(a). It is suggested thinner space layer will reduce fluctuation of transmission caused by F-P interference. In our work, a typical value of 300 nm is used and introduces 30% loss of the THz wave. Fig. S2(b) shows the SiO_2 thickness dependent mapping of THz wave transmittance (T'_{in} / T'_{ot}) for bare SiO_2/Si substrate. F-P interference can't be avoided in the THz range for the thin substrate on the scale of micrometer. As an example, the relative transmission ranges from 0.47 to 1.15 when Si is 200 μm in thickness on the top panel of Fig. S2(b). This interference will influence the actual broad-band manipulation with magnetoplasmons. As a result, the proper thickness selection will become a very important factor for the design of graphene based THz modulators and isolators.

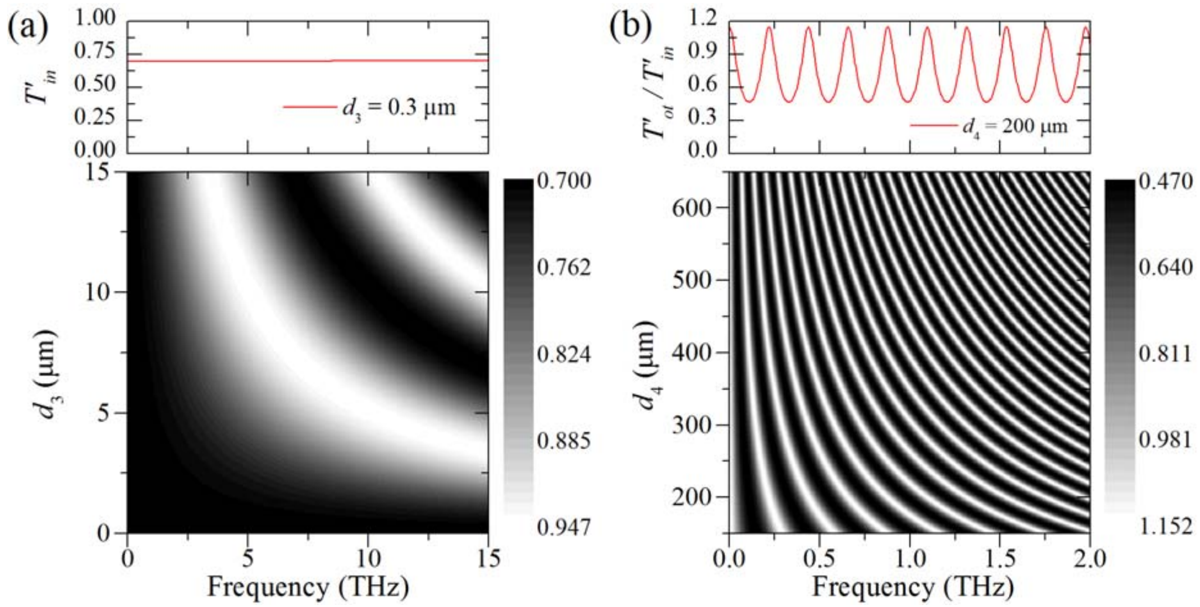

Fig. S2 (a) Bottom: shows the SiO_2 thickness dependent mapping of THz wave transmittance T'_{in} for bare SiO_2/Si substrate; Top: THz wave transmittance with SiO_2 of 300 nm in thickness. (b) Bottom: Si thickness dependent mapping of relative THz wave transmission T'_{in} / T'_{ot}; Top: relative THz wave transmission with a silicon substrate of 200 μm in thickness.

For better transmittance of the devices with thin substrates, suitable thicknesses of silicon substrate should be used for different THz applications in certain frequencies. For example, at different THz atmospheric windows below 1 THz, Table S2 summarizes the thicknesses of silicon d_4 (Between 180 μm and 650 μm) for F-P interference peaks occur.

Table S2 Thicknesses of SiO_2 and Si for F-P interference peaks at different THz atmospheric windows below 1 THz

THz Atmospheric Windows (THz)	SiO_2 d_3 (nm)	Si d_4 (μm) (180 < d_4 < 650)
0.12	300	365
0.225	300	195, 390, 585
0.3	300	292, 439, 585
0.35	300	251, 376, 501, 627
0.41	300	214, 321, 428, 535, 642
0.67	300	196, 262, 327, 393, 458, 524, 589
0.85	300	155, 206, 258, 310, 361, 413, 464, 516, 568, 619

We consider the F-P interference caused by the thin substrate with the thickness comparable to the THz wavelength. We propose proper selections of the thicknesses of substrate will become an effective solution for better transmittance performance of both modulator and isolator. For THz applications in certain frequencies,[1] we can find F-P interference peaks occur in certain thicknesses of Si substrate (see Table S2). As an example in THz communication, 0.12 THz wireless links have been developed.[1,2] Fig. S3(a) shows the real transmittance of graphene on SiO_2 spacer and Si substrate at frequency centered at 0.12 THz with tuning voltages –10 V and –80 V. The thickness of SiO_2 is 300 nm, which ensures a steady transmission in a broad THz band. When the thickness of Si is set to 365 μm, F-P interference peaks occurs. A uniform transmittance is observed, and this graphene-based THz modulator exerts effective intensity modulation depth 15.7 % with electric tunability. The modulation value can be extended to 19.4 % for better graphene samples with the scattering rate of 10 meV. A Faraday rotation angle of 3.8 degrees can also be obtained for THz isolator applications.

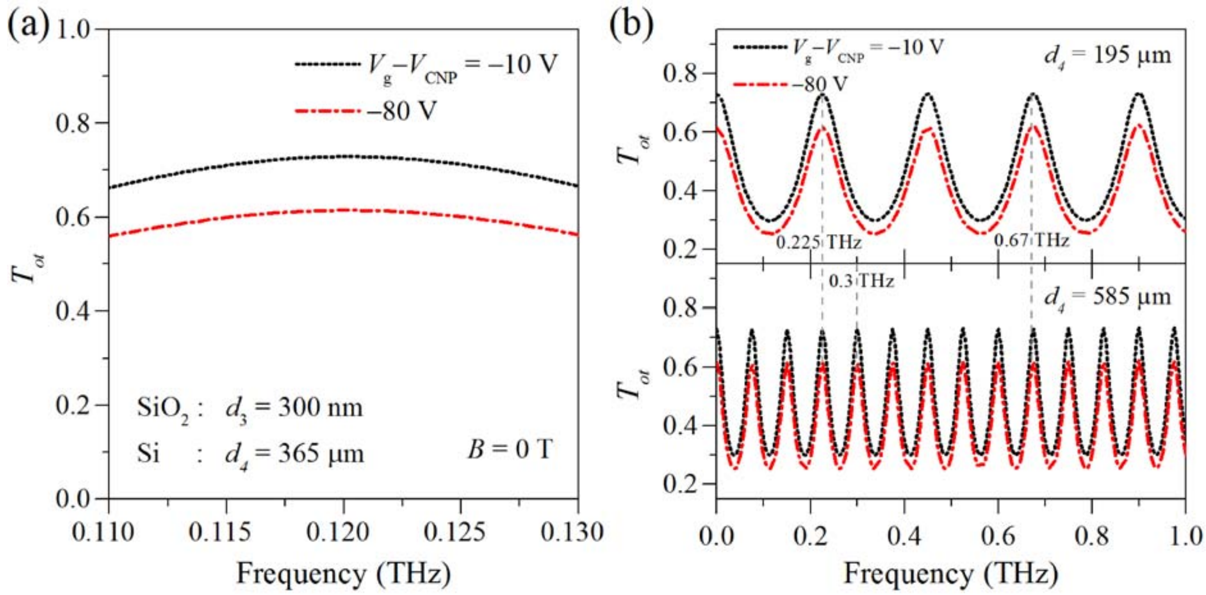

Fig. S3 (a) The real transmittance of graphene on SiO_2 of 300 nm in thickness and Si of 365 μm in thickness in the frequency around 0.12 THz with different tuning voltages –10 V and –80 V. (B= 0 T) (b) Top: The real transmittance of graphene on SiO_2 of 300 nm in thickness and Si substrate of 195 μm in thickness in the frequency region below 1 THz. Bottom: The real transmittance of graphene on SiO_2 of 300 nm in thickness and Si substrate of 585 μm in thickness.

Appropriate choices of the substrate thickness d_4 will achieve some useful multi-band devices. For example, 0.225 THz, 0.3 THz, 0.67 THz are some THz atmospheric windows. Fig. S3(b) show that with a Si substrate of 195 μm in thickness, THz modulator can work well at 0.225 THz and 0.67 THz. With a Si substrate of 585 μm in thickness, it can be used at 0.225 THz, 0.3 THz and 0.67 THz.

S3 Maximum Faraday rotation angle

The giant Faraday rotation originating from the cyclotron effect in the classical regime by intraband transitions in graphene. High carrier density but modest magnetic fields are needed for the maximum value. Fig. S4 shows the maximum Faraday rotation angle at different doping concentrations as well as the magnetic fields (B) needed for the maximum Faraday rotation angle. These two parameters have the same growth trend with the applied voltage. The maximum θ_F rises from 1.39 to 3.77 degrees, corresponding to a magnetic field from 2.27 T to 6.65 T, under the gate voltage –10 V to –80 V.

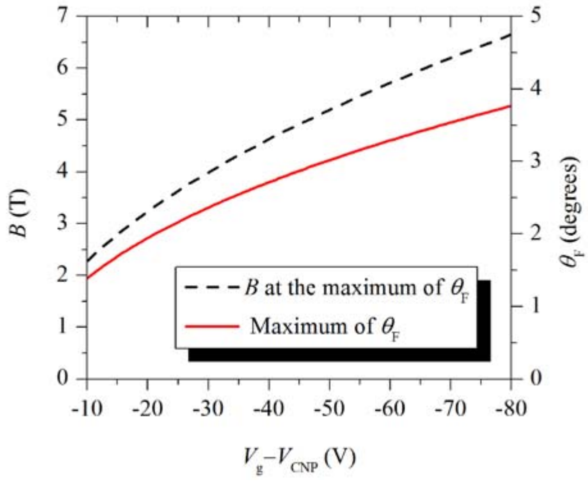

Fig. S4 Black dash line is the magnetic field needed for the maximum Faraday rotation angle with gated voltage from –10 V to –80 V; Red solid line is the maximum Faraday rotation angle with the same gated voltage.

References

1. M. Tonouchi, *Nat. Photonics*, 2007, **1**, 97-105.
2. A. Hirata, T. Kosugi, H. Takahashi, R. Yamaguchi, F. Nakajima, T. Furuta, H. Ito, H. Sugahara, Y. Sato and T. Nagatsuma, *IEEE Trans. Microwave Theory Technol.*, 2006, **54**, 1937-1944.