Tunable multistate terahertz switch based on multilayered graphene metamaterial

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Abstract
We proposed plasmonic effect-based narrow band tunable terahertz switches consisting of multilayered graphene metamaterial. Though several terahertz optical switches based on metamaterials were previously reported, these switches had complicated fabrication processes, limited tunability, and low modulation depths. We designed and simulated ingenious four- and eight-state terahertz optical switch designs that can be functional for multimode communication or imaging using the finite-difference time-domain simulation technique. The plasmonic bright modes and transparency regions of these structures were adjusted by varying the chemical potential of patterned graphene layers via applying voltage in different layers. The structures exhibited high modulation depth and modulation degree of frequency, low insertion loss, high spectral contrast ratio, narrow bandwidth, and high polarization sensitivity. Moreover, our proposed simple fabrication process will make these structures more feasible compared to previously reported terahertz switches. The calculated modulation depths were 98.81% and 98.71%, and the maximum modulation degree of frequencies were ∼61% and ∼29.1% for four- and eight-state terahertz switches, respectively. The maximum transmittance in transparency regions between bright modes and the spectral contrast ratio were enumerated to be 95.9% and ∼96%, respectively. The maximum insertion losses were quite low with values of 0.22 dB and 0.33 dB for four- and eight-state terahertz switches, respectively. Our findings will be beneficial in the development of ultrathin graphene-based multistate photonic devices for digital switching and sensing in the terahertz regime.

Keywords Terahertz · Metamaterial · Graphene · Plasmonics · Terahertz switch · Multistate switch · Finite-difference time-domain

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1 Introduction

Due to its distinctive properties, electromagnetic (EM) waves in the terahertz (THz) frequency regime have inspired tremendous academic and technological interest because of their various applications, including wireless communication, chemical detection, biomedical imaging, and interconnect optoelectronic devices (Tonouchi 2007; Nagatsuma et al. 2016; Zhang et al. 2021; He et al. 2022; Leng et al. 2022; Peng et al. 2020). Over the last decade, many techniques, including those based on active metamaterials and two-dimensional materials, have been studied to control electromagnetic wave propagation from radio to THz frequency (Zaytsev et al. 2019; Tao et al. 2011; Wang and Yang 2018). Graphene, a highly conductive single-atom-thick material with a hexagonal shape of carbon atoms, exhibits long-lived plasmon excitation, outstanding low loss, and customizable properties. These characteristics make graphene metamaterial-based optical switches advantageous in switching schemes with enhanced efficiency. Consequently, several experimental and theoretical works on graphene metamaterial-based infrared optical switches, where plasmonic effect can eliminate the opaque effect of the medium to the electromagnetic wave using surface plasmon polariton (SPP), were reported (Sarker et al. 2021; Zhang et al. 2020, 2008; Hu et al. 2016; Liu et al. 2020; Khazaee and Granpayeh 2018; Li et al. 2020; Luo et al. 2016). In particular, optical switches are essential elements in various applications such as modern communication system (Reichel et al. 2018) and signal measurement (Song et al. 2017).

Depending on the interaction between the electric field of incoming light and plasmonic structure, two modes can exist. The mode, which is strongly coupled to the incident light reducing the transmission due to the localization of the light field around the graphene nanoribbon structures, is the bright mode. Another mode is a dark mode which is weakly coupled to the incoming light creating transparency in the transmission spectrum. A transmission transparency of 90% and 70% between two bright modes was reported by Tang et al. (2019) and Ou et al. (2020), respectively for THz optical switch using metal-based metamaterial on dielectric and silicon substrate. However, tuning resonant frequencies in these structures were not possible without modifying the physical structures. In contrast, the surface conductivity of the graphene metamaterials can be modulated directly without changing structural parameters by applying voltage. Habib et al. (2018) introduced gold strips on top of graphene and the structure had a spectral contrast ratio of 82% at the mid-infrared region. Li et al. (2018) reported a structure with left-right electrodes instead of conventional top-bottom electrodes. Though such designs allowed the transmittance of terahertz (THz) signal to be regulated by a voltage source, the performance parameter modulation depth (MD) was low (89%) compared to previous studies. MD of 92% was achieved by Khazaee and Granpayeh (2018) at mid-infrared frequency regime, but transmission intensity between two bright modes was very poor (∼70%) for an optical switch. Cascaded two-state switch elements allowed for more connection through concatenating additional switching states; however, achieving high extinction ratios in such two-state switch elements had proven problematic than multistate switch (Stabile et al. 2012). Although there were very limited reports of four-state optical switch in the literature, eight-state switch in THz regime is yet to be explored. Moreover, there is scope for significant improvement in switch performance for THz communication and sensing applications in terms of performance parameters.

In this paper, we proposed high-performance four- and eight-state narrow band THz optical switches based on the two- and three-patterned layer of graphene sheets,
respectively, utilizing the concept of the SPP phenomenon. The optical switches were realized by tuning chemical potential in the patterned graphene layers on polymethyl methacrylate (PMMA) and consequently producing multiple plasmonic modes. We optimized the designs and evaluated the performance of these devices using the finite-difference time-domain (FDTD) method. Tuning of the chemical potentials was accomplished by adjusting the surface conductivity of graphene via voltage sources. Additionally, we performed a polarization sensitivity analysis of our proposed narrow band THz switches and proposed a viable fabrication process. A comparative analysis of the performance parameters of our switches and recently demonstrated graphene metamaterial-based optical switches were conducted. This study will pave a new way to design and fabricate THz optical switches.

2 Methodology

Patterned graphene monolayer on both sides of PMMA constituted our four-state THz switch design as can be seen in Fig. 1a. The monolayer graphene can be grown using the chemical vapor deposition (CVD) process. The top graphene layer consisted of a periodic array of strips of graphene nanoribbon (GNR) and air holes. The bottom layer consisted of a single rectangular air hole which can be created using helium ion beam lithography (HIBL) technique. A suggested fabrication process is provided in Supplementary Information. The length and width of PMMA were set to be 3 μm. The thickness of PMMA layers was chosen 2 μm to avoid near-field interaction (See Fig. S3 in Supplementary Information for details) and Fabry-Perot multi-reflections (Sarker et al. 2021). The nanoribbon strip width, w of the top graphene layer was 0.01 μm with pitch distance, d of 0.02 μm, and air

![Fig. 1](image_url)

*Fig. 1*  
(a) Illustration of proposed four-state graphene metamaterial based THz switch under x-polarized THz electric field propagating along z direction. Magnified view is depicted in inset where, d = 0.02 μm, w = 0.01 μm, l = 2.5 μm, length and width of PMMA = 3 μm, h = 2 μm, and i = 0.15 μm.  
(b) Three dimension view of eight-state graphene metamaterial based THz switch with geometrical parameters: h = 2 μm, l = 2.5 μm, length and width of PMMA = 3 μm, i = j = 0.15 μm, d = 0.02 μm, w = 0.01 μm. V_g is the gate voltage used to tune the chemical potential of n-th graphene layer. The gate voltage can be applied using voltage sources connected to the graphene layers through metal contacts.
hole length, l of 2.5 μm. On the top graphene layer, there are 12 periodic air holes of 0.01 μm width and 11 nanoribbon strips, one after each airhole. Therefore, the overall width of the periodic array is 0.21 μm. Detailed analyses of resonant frequency dependency on w and d were performed elsewhere (Sarker et al. 2021). The rectangular air hole of the bottom graphene layer width, i was set to be 0.15 μm. The graphene layers were connected to voltage sources via metal contacts to vary the chemical potential, μcn of the corresponding n-th graphene layers.

Three layers of patterned graphene on PMMA layer comprised our proposed eight-state THz switch design as illustrated in Fig. 1b. A similar fabrication technique can be used to form patterns on three graphene layers. We provided a detailed fabrication method in Supplementary Information. Two PMMA layers had identical height (h) of 2 μm. The patterned top graphene layer had similar parameters as four-state switch’s top graphene layer. The middle and bottom graphene layers had a rectangular air hole having a width of i = j = 0.15 μm. Voltage sources were connected through metal contacts to allow the tuning of μcn. The structures were on top of a PMMA layer and air was the dielectric medium above the top graphene layer.

The study was conducted using 3D FDTD numerical analysis technique. Periodic boundary conditions were employed in the x- and y-directions. In the positive and negative z-directions, the steep angle perfectly matched layer (PML) boundary condition was adopted. To avoid light reflection from the PML border, the thickness of the PML layer was designed to be larger than the source’s peak wavelength. We used a non-uniform conformal mesh. A plane wave THz light was incident from the top along the z-direction. The transmission spectra were recorded by a power monitor at the bottom of the structure.

The well-known Kubo’s formulation was employed to simulate the surface conductivity of graphene which consists of intraband and interband transitions of electron (Hanson 2008; Casiraghi et al. 2007; Li et al. 2018). The detailed formulation can be found elsewhere (Sarker et al. 2021). The conductivity of graphene, σ can be obtained by Rouhi et al. (2012),

$$\sigma = \frac{ie^2E_f}{\pi\hbar^2(\omega + i\tau^{-1})},$$  \hspace{1cm} (1)

where τ = μEf/eVF 2 is the carrier relaxation time. μ, ω, e, h, Ef, and VF are the mobility of graphene, the angular frequency of the incident light, the electron charge, the reduced Planck constant, the Fermi level of graphene, and the Fermi velocity, respectively. This formulation of the optical conductivity is a good approximation for graphene on substrate without considering the out-of-plane optical conductivity (Xu et al. 2021). For all simulations, the temperature was set to be 300 K and Ef was approximately equal to μcn (Sarker et al. 2021). The relaxation time, τ for good quality graphene can be more than 10 ps (Bolotin et al. 2008). Here, we assumed that τ = 2 ps. The chemical potential of graphene layers was tuned by adjusting the surface conductivity of graphene via voltage sources.

3 Results and discussion

Interaction between incoming plane wave and patterned graphene layer resulted in plasmon resonance on the surface of graphene layer which attenuates light by scattering. Moreover, transmission of light through the structure was blocked at a certain resonant frequency because of strong plasmonic interaction. Hence, each patterned graphene layer on PMMA
act as an attenuating medium resulting in a plasmonic bright mode at a certain resonant frequency. The transmission spectra formed in different GNR metamaterial layers were depicted in Fig. 2. The GNR gave rise to the plasmonic bright mode as shown in Fig. 2a (Lorentz curve shown in black color). The GNR layer with rectangular air hole produced a plasmonic bright mode (Lorentz curve shown in red color). When the two structures were merged in a structure as top and bottom layers, coupling of the bright modes blue-shifted the plasmonic bright mode originated from the air hole as can be seen in Fig. 2a (blue curve). Here, the chemical potential of graphene layer was set to be 0.4 eV for all layers. Similarly, three engineered layers of graphene illustrated plasmonic modes as shown in Fig. 2b. To get two distinguishable bright plasmonic modes, the patterned graphene layers at different chemical potentials were utilized as shown in Fig. 2c and d.

We engineered two and three patterned graphene layers to create two and three stymies of light transmission and formed narrow transparency windows between them (See Fig. S2 of Supplementary Information). It is apparent from the reflectance and absorption spectra for four- and eight-state THz switches that reflection and absorption in these transparency windows were very low (Fig. S2 of Supplementary Information).

Fig. 2  a Transmission spectra of only GNR strips, only rectangular air hole in graphene, and structure shown in Fig. 1a. Here, the chemical potential of graphene was set to be 0.4 eV. b Transmission spectra of only GNR strips, only rectangular air hole in graphene, and structure shown in Fig. 1b. Transmission spectra of c four- and d eight-state switching schemes are depicted for different switching states. Plasmonic bright modes in graphene layer are shown in inset. Here, “0” and “1” represent plasmonic bright mode (off state) and plasmonic dark mode (on state), respectively.
3.1 Four-state switching scheme

To achieve four-state switching scheme, we utilized localized plasmon resonance phenomenon in two stacked patterned graphene layers. In order to get a better comprehension of plasmonic effect, the field distributions of two dips are presented in Fig. 3a and b. The light field was localized primarily around the bottom patterned graphene layer at resonant frequency of 3.357 THz, as shown in Fig. 3a. Similarly, the top patterned graphene layer had localized electric field at 5.439 THz creating the bright plasmonic mode. Thus, localized light fields were observed at near top surface of graphene layer (See Fig. S3 in Supplementary Information). A single transparent window appeared between two bright plasmonic modes. When x-polarized light was incident on the entire structure, a transparent transmission window with transmission intensity < 96% emerge at the valley of the Lorentz curve as can be seen in Fig. 3c. Transition states of the switch using different chemical potentials are listed in Table 1. Different combinations of chemical potentials were employed at two patterned graphene layers to achieve different transition states as can be seen in Table 1.

| State | $\mu_{c_1}$ (eV) | $\mu_{c_2}$ (eV) | Illustration |
|-------|------------------|------------------|--------------|
| 00    | 0.5              | 0.2              | Fig. 3c      |
| 01    | 0                | 0.2              | Fig. 3d      |
| 10    | 0.5              | 0                | Fig. 3e      |
| 11    | 0                | 0                | Fig. 3f      |
Figure 3c–f depict the various states of the THz switch. We represented plasmonic bright mode (off state) and plasmonic dark mode (on state) by “0” and “1”, respectively. The chemical potentials were 0.5 eV and 0.2 eV, 0 eV and 0.2 eV, 0.5 eV and 0 eV, and 0 eV and 0 eV for OFF - OFF (00), OFF - ON (01), ON - OFF (10), and ON - ON (11) states, respectively. The OFF - OFF (00) state has two plasmonic bright modes at 3.357 THz and 5.439 THz, while the ON - ON (11) state has two plasmonic dark modes at 3.357 THz and 5.439 THz. To determine the performance of the THz switch, MD was calculated by Liu et al. (2020),

$$MD = \frac{T_{on} - T_{off}}{T_{on}}. \quad (2)$$

Here, $T_{on}$ and $T_{off}$ denote the magnitude of transmittance in the on and off state, respectively. Our four-state switch structure yielded MDs of 95.66% and 98.81% at resonant frequencies of 3.357 THz and 5.439 THz, respectively.

### 3.2 Eight-state switching scheme

An eight-state THz switch consisting of three patterned graphene layers on PMMA layer was designed using localized plasmonic effect. Two transparent windows emerged at the valley of the Lorentz curves between three plasmonic bright modes due to the surface conductivity of graphene layers using different chemical potentials. Transition states of eight-state narrow band THz switch using different chemical potentials of graphene layers are listed in Table 2. The chemical potentials of 0.2 eV, 0.3 eV, and 0.35 eV were employed via voltage sources by changing the surface conductivity of graphene. Two transparent windows with maximum transmission intensity of ~85% at the valley of Lorentz curves appeared when an x-polarized light was incident from the top along the z direction. To analyze the plasmonic effect extensively, the field distributions of three dips were delineated in Fig. 4. Localized electric field distributions at the top, middle, and bottom graphene layers were presented when the THz beam frequencies were 4.650 THz, 2.285 THz, and 3.385 THz, respectively (See Fig. S4 in Supplementary Information for xz and yz cross-section of E-field distributions).

The transmission spectra of the eight-state THz switch at all possible states are shown in Fig. 5. Three plasmonic bright modes of the “000” state appeared at resonant frequencies of 2.285 THz, 3.385 THz, and 4.650 THz. On the contrary, three plasmonic dark modes of the “111” state existed at resonant frequencies of 2.285 THz, 3.385 THz, and 4.650 THz.

| State | $\mu_{c1}$ (eV) | $\mu_{c2}$ (eV) | $\mu_{c3}$ (eV) | Illustration |
|-------|----------------|----------------|----------------|--------------|
| 000   | 0.35           | 0.3            | 0.2            | Fig. 5a      |
| 001   | 0              | 0.3            | 0.2            | Fig. 5b      |
| 010   | 0.35           | 0.3            | 0              | Fig. 5c      |
| 011   | 0              | 0.3            | 0              | Fig. 5d      |
| 100   | 0.35           | 0              | 0.2            | Fig. 5e      |
| 101   | 0              | 0              | 0.2            | Fig. 5f      |
| 110   | 0.35           | 0              | 0              | Fig. 5g      |
| 111   | 0              | 0              | 0              | Fig. 5h      |
The calculated MD was 97.47%, 95.33%, and 98.71% at resonant frequencies of 2.285 THz, 3.385 THz, and 4.650 THz, respectively. Additionally, the cross-sectional views of the field distributions for “010” and “111” states at three graphene patterned layers are provided in Supplementary Information (See Figs. S5-S8).

3.3 Plasmon tuning and performance analysis

To tune the resonant frequency without any structural modification, the surface conductivity of graphene can be varied by changing $\mu_c$ in the wide range of 0 eV – 1.3 eV via appropriate external gate voltage $V_g$. Similar level of voltages were reported in previous studies (Fallah et al. 2019; Zhang et al. 2020; Liu et al. 2020, 2020; Zhang et al. 2021). The relationship of $V_g$ with $\mu_c$ is given by Ju et al. (2011).
Here, $\varepsilon_{\text{PMMA}}$ is the permittivity of the PMMA layer. By changing the $\mu_c$ of graphene layers using external voltage sources as shown in Figs. 1a and b, the resonant frequency can be widely tuned in the THz frequency regime. Here, we expect that the parasitic impedance due to metal contact to be very small and hence, it was ignored. A color map of transmittance, shown in Fig. 6a, for four-state THz switch at different chemical potentials displays the evolution of plasmonic modes. It is evident from Fig. 6a that the plasmonic bright modes in the transmission spectra are blue-shifted with the increase of chemical potentials. The chemical potentials of the top and bottom graphene layers were varied separately as can be seen in Fig. 6b and c. Noteworthy, the lower frequency dip exhibited a blue shift when the chemical potential of the top graphene layer was varied from 0.6 to 0.95 eV. Similarly, the higher frequency dip showed a blue-shift when the chemical potential of the bottom graphene layer was changed from 0.3 to 0.65 eV. The modulation degree of frequency, MDF a performance parameter that describes the frequency tailoring capability of the switch, can be expressed mathematically by Liu et al. (2020),

$$\text{MDF} = \frac{|f_{\text{max}} - f_{\text{min}}|}{f_{\text{min}}}.$$  \hspace{1cm} (4)

Here, $f_{\text{max}}$ and $f_{\text{min}}$ are the frequencies of maximum and minimum modulated dips of transmission spectra, respectively. The MDFs of first and second resonant dips were calculated to be $\sim56\%$ and $\sim61\%$ which is high compared to previous report (Li et al. 2020). Additionally, to evaluate the contrast of transmission between the transparent region and the bright plasmon mode, we calculated spectral contrast ratio, $S_{\text{con}}$ given by Yan et al. (2017),

$$S_{\text{con}} = \frac{T_{\text{transparent}} - T_{\text{bright}}}{T_{\text{transparent}} + T_{\text{bright}}},$$  \hspace{1cm} (5)

where $T_{\text{transparent}}$ and $T_{\text{bright}}$ are the average transmittance of the transparent region(s) and plasmonic bright modes. $S_{\text{con}}$ of our proposed four-state THz switch was 96.2\% which indicated impressive sensitivity of our proposed switch.

The dependencies of transmission at the transparent regions and plasmonic bright modes with respect to frequency are given in Supplementary Information (see Fig. S9). A

![Fig. 6](image_url)

**Fig. 6** a) Evolution of plasmonic bright modes at different chemical potentials. Here, two plasmonic bright modes, as well as transparent region between bright modes, are blue-shifted by increasing chemical potentials of graphene layers. b) Customization of the lower frequency dip (plasmonic bright mode) keeping $\mu_{c_1}$ at 0.8 eV. c) Frequency tuning of the higher frequency dip (plasmonic bright mode) keeping $\mu_{c_2}$ at 0.3 eV.
visualization of the evolution of plasmonic bright modes for eight-state THz switch with the variation of chemical potentials are depicted in Fig. 7a. The plasmonic bright modes were blue shifted as can be seen in Fig. 7b–d. The calculated MDFs were 27.08%, 29.1%, and 11.97% for the three bright modes. Calculated $S_{con}$ was 96.3% for eight-state THz switch.

Insertion loss, an important performance parameter of infrared optical switches, was calculated by $-10 \log_{10}(T_{on})$ (Zubair et al. 2016). Insertion loss was enumerated to be 0.22 dB and 0.33 dB for four- and eight-state THz switches, respectively. These values are substantially low compared to that of previously reported optical switches (Chu and How Gan 2013; Li et al. 2020, 2018; Khazaee and Granpayeh 2018). Moreover, we obtained extinction ratio, $ER = 10 \log_{10}(T_{on}/T_{off})$ of 19.67 dB and 18.89 dB for four- and eight-state THz switches, respectively.

Furthermore, we quantified the dephasing time, $\tau_\phi^{-1} (= 2h/FWHM)$ (Ahmadivand et al. 2016) for the induced deepest dip of our proposed devices. The estimated dephasing times were 2.27 ps and 1.87 ps for four- and eight-state THz switches, respectively. Figure 8a depicts transmitted THz wave in the time domain for incident light and different states of

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**Fig. 7** a Evolution of plasmonic bright modes at different chemical potentials. Here, three plasmonic bright modes as well as two transparent regions between bright modes are blue-shifted by increasing chemical potentials of graphene layers. b Frequency variation of the first plasmonic bright mode considering $\mu_c = 0.4$ eV and $\mu_c = 0.2$ eV. c Frequency variation of the second plasmonic bright mode considering $\mu_c = 0.4$ eV and $\mu_c = 0.15$ eV. d Frequency variation of the third plasmonic bright mode considering $\mu_c = 0.15$ eV and $\mu_c = 0.2$ eV

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eight-state THz switch. The electric field of the “000” state attenuated the light at resonant frequencies. It is evident from Fig. 8a that when the states were changed from the “000” state to the “111” state, the deviation of transmitted THz electric field reduced.

The polarization of the incident THz wave was varied for the eight-state optical switch which is illustrated in Fig. 8b. It is evident from our calculation that all three plasmonic bright modes are polarization dependent (see Fig. S10 in Supplementary Information). The polarization angle, \( \theta \) is an angle between the x-axis and the direction of the light polarization. We observed the highest normalized transmission at \( \theta = 0^\circ \) because of maximum attenuation of THz wave at a resonant frequency while the opposite scenario is applicable at \( \theta = 90^\circ \). In this polar plot, \( \theta \) was swept from x polarized light to y polarized light.
polarization angles for eight-state THz switch. We observed polarization dependency transmission with the highest transmission for $\theta = 0^\circ$ and the lowest transmission for $\theta = 90^\circ$. Hence, we can conclude that the presented THz optical switches are highly polarization sensitive.

3.4 Comparative analysis

Table 3 demonstrates the comparison of performance parameters between our proposed THz switches and previously reported THz switches. A graphene ribbon array switch that operated in the mid-infrared regime, had the MD of 70% along with high insertion loss (Chu and How Gan 2013). Wei et al. introduced a graphene THz metamaterial structure with considerably higher MD (96.2%) (Wei et al. 2016). This structure had narrower bandwidth than the array structure (Chu and How Gan 2013). There are previous reports on graphene micro-cavity (Li et al. 2020) and graphene-based non-volatile (Li et al. 2018) THz switch that had similar bandwidth compared to our switches. However, MD and insertion loss were much lower.

The grating structure proposed by Khazaee et al. had a decent MD of 92%, but high insertion loss that operated in the infrared regime (Khazaee and Granpayeh 2018). In terms of MDF, the graphene micro-cavity switch (Li et al. 2020) had 30%, which is comparable to our eight-state switch. But our four-state switch had an MDF of almost double (∼61%). In comparison to all of the previously reported work, our proposed four- and eight-state switches had narrow bandwidth functioning in the THz regime with significantly higher MDs of 98.81% and 98.71% for both four- and eight-state switches, respectively.

4 Conclusions

In this work, we proposed and numerically analyzed plasmonic effect based four- and eight-state narrow band THz switches that had high MD, extremely low insertion loss, wide range MDF, and high spectral contrast ratio. Because of the strong interaction between patterned graphene layers and incoming light, plasmonic bright modes originated. We exploited these interactions of plasmonic bright modes and dark modes in patterned multilayer of graphene on PMMA layer to design the THz switches. The modulation of surface conductivity by varying chemical potentials of different graphene layers resulted in the modulation of plasmonic bright modes. Consequently, a narrow transparent band between bright modes emerged. High values of transmission intensities between two bright modes were obtained with maximum MDs of 98.81% and 98.71% for our proposed four- and eight-state THz switches, respectively. Interestingly, feasible wide tuning of the bright modes was demonstrated by adjusting the applied voltage of graphene metamaterial without any structural modification. We obtained exceedingly low insertion losses of 0.22 dB and 0.33 dB with wide MDFs. Moreover, the bandwidth at operating frequencies was as narrow as a few hundreds of GHz. This study will put forward a basis for designing and manufacturing multimode plasmonic switches and modulators in the THz frequency regime for communication and sensing applications.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11082-022-04426-9.
| Description of structure | Operating wavelength regime | Relaxation time (ps) | Band - width (THz) | MD (%) | MDF (%) | Insertion loss (dB) | References |
|--------------------------|-----------------------------|----------------------|-------------------|--------|--------|-------------------|------------|
| Graphene ribbon array    | Mid infrared                | 0.3                  | 1.87              | < 70   | –      | 4.77              | (Chu and How Gan 2013) |
| Grating structure        | Infrared                    | 0.93                 | –                 | 92     | –      | 1.55              | (Khazaee and Granpayeh 2018) |
| Graphene metamaterial    | Terahertz                   | –                    | 1.1               | < 96.2 | –      | –                 | (Wei et al. 2016) |
| Graphene micro-cavity    | Terahertz                   | >2                   | 0.2               | < 90   | 30     | 0.36              | (Li et al. 2020) |
| Graphene based non-volatile | Terahertz               | 40                   | 0.12              | 89     | –      | 0.46              | (Li et al. 2018) |
| Four-state switch        | Terahertz                   | 2                    | 0.14              | < 98.81| ~ 61   | 0.22              | This work |
| Eight-state switch       | Terahertz                   | 2                    | 0.17              | < 98.71| 29.1   | 0.33              | This work |

Table 3 Performance comparison of the proposed THz switches
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Author Contributions Dip Sarker and Partha Pratim Nakti conducted the investigation, performed the analysis, wrote the main manuscript text, and prepared figures. Dip Sarker and Partha Pratim Nakti contributed equally to this work. Md Ishfak Tahmid and Md Asaduz Zaman Mamun conducted the investigation and wrote the main manuscript text. Ahmed Zubair supervised and administered the work and wrote the main manuscript text. All authors reviewed the manuscript.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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