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Monolithic Graphene-qBIC Resonators for Electrically Tunable Terahertz Modulation

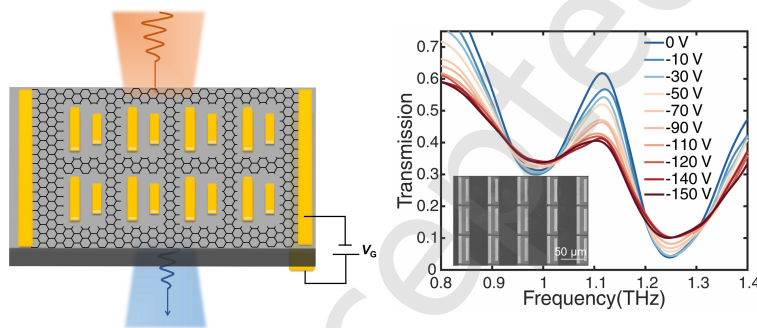
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This work demonstrates a novel terahertz modulator based on monolithic graphene-quasi-bound-state-in-the-continuum resonator platform, by integrating patterned graphene within symmetry-broken double-rod metallic resonators, the dissipative loss of high-Q resonance can be continuously controlled through electrostatic gating. The fabricated modulator achieves a modulation depth of 35%, a resonance bandwidth of 0.12 THz centered at 1.1 THz, an equivalent Q factor of 9.28, a 3 dB modulation speed of 14 kHz, and a low insertion loss of 2.08 dB. These results demonstrate balanced optimization of key modulation metrics in a compact, planar architecture, providing a practical route toward active THz photonic devices.

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ABSTRACT: Terahertz (THz) modulators are essential components for dynamic wavefront control in imaging, sensing, and wireless communication systems. However, practical THz modulators require simultaneous optimization of multiple functional metrics, including modulation depth, resonance quality, insertion loss, switching speed, and device integration, which are often difficult to balance within a single device architecture. Graphene is an attractive active material because of its electrical tunability, high carrier mobility, and compatibility with planar integration, but its intrinsically weak interaction with THz waves limits the modulation efficiency of pristine monolayer devices. Here, we demonstrate a monolithic graphene-quasi-bound-state-in-the-continuum (qBIC) resonator platform that addresses this multidimensional performance trade-off. By integrating patterned graphene within symmetry-broken double-rod metallic resonators, the dissipative loss of a high-Q qBIC resonance can be continuously controlled through electrostatic gating. The fabricated modulator achieves a modulation depth of 35%, a resonance bandwidth of 0.12 THz centered at 1.1 THz, an equivalent Q factor of 9.28, a 3 dB modulation speed of 14 kHz, and a low insertion loss of 2.08 dB. These results demonstrate balanced optimization of key modulation metrics in a compact, planar architecture, providing a practical route toward active THz photonic devices.

KEYWORDS: terahertz optics, graphene, bound states in the continuum, amplitude modulation

1. Introduction

Terahertz (THz) radiation, typically defined as the spectral range from 0.1 to 10 THz, bridges microwave and far-infrared frequencies[1]. Owing to its distinctive spectroscopic and electromagnetic properties, the THz regime has enabled applications in high-resolution imaging[2, 3], biomedical sensing[4-6], and next-generation wireless communications[7-9]. The practical implementation of these technologies requires efficient THz modulators capable of dynamically controlling amplitude, phase, and polarization. As basic functional elements in THz systems, modulators rely on active materials that respond to both incident THz radiation and external electrical stimuli[10-15]. Conventional THz modulators based on micro-electromechanical systems or phase change materials often suffer from limited modulation speed, while semiconductor-based modulators are typically too bulky[16-18]. Consequently, these existing approaches remain unsuitable for realizing compact frequency selective terahertz modulators that require both high speed and high integration density. In this context, graphene is particularly attractive because of its high carrier mobility, electrically tunable carrier density, and compatibility with large-area, CMOS-compatible processing[19-25]. Nevertheless, pristine

monolayer graphene exhibits a nonresonant Drude-like intraband response, resulting in a limited optical cross-section and insufficient modulation efficiency for practical use[26].

Integrating graphene with subwavelength resonators provides an effective strategy for enhancing light-matter interactions and improving THz modulation performance[27]. Resonant structures based on electromagnetically induced transparency[28-30], charge-transfer plasmon modes[31], and surface plasmon-cavity hybrid states[32] have been explored to enhance local fields and increase tunability. However, THz modulators must be evaluated using several coupled metrics, including modulation depth, switching speed, insertion loss, device footprint, and the quality factor (Q factor). A critical challenge arises from the fact that optimizing one functional metric often necessitates sacrificing others. For example, many reported monolayer graphene modulators are highly compact yet remain limited by low-Q resonances, whereas bulk-cavity approaches can improve the Q factor at the expense of device integration and compactness[33]. Modulators intended for practical applications must demonstrate a balanced performance across these metrics. Thus, a planar architecture that combines strong resonant field enhancement with electrical tunability and low

dissipative loss remains highly desirable.

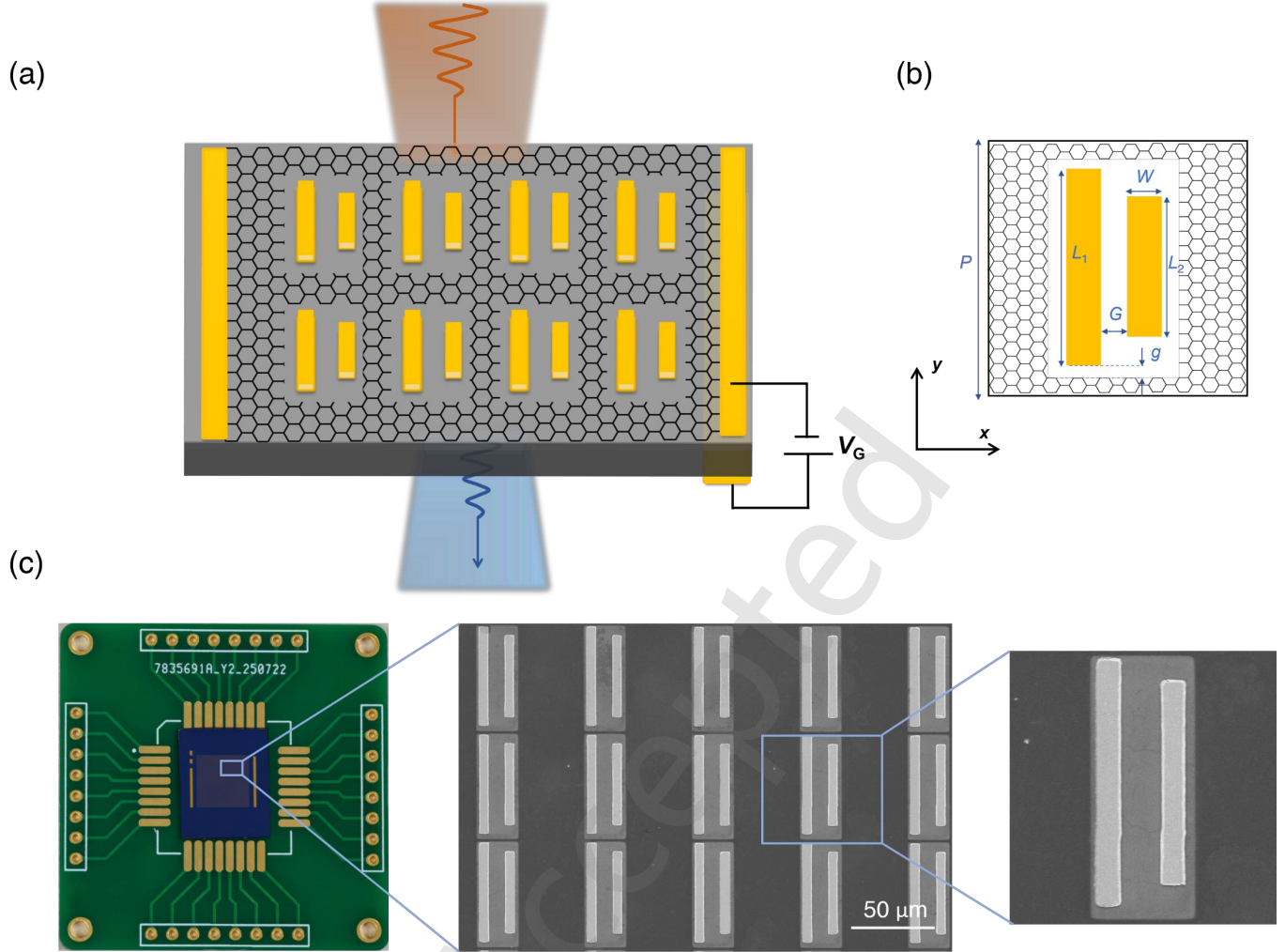


Figure 1. Device architecture of the graphene DRMA modulator. (a) Schematic illustration of the graphene-based THz modulator. (b) Unit cell geometry of the hybrid qBIC architecture. The gap parameter denotes the lateral distance between the DRMAs and the edge of the graphene window. (c) Top-view optical micrograph and scanning electron microscope (SEM) image of the fabricated modulator.

In this work, we demonstrate a monolithic active THz modulator based on graphene-integrated quasi-bound states in the continuum (qBICs). Bound states in the continuum are nonradiating dark modes that remain decoupled from free-space radiation despite lying within the radiation continuum[34-38]. By introducing structural asymmetry into a double-rod micro-antenna (DRMA) system, we convert the ideal BIC into a radiatively accessible high-Q qBIC mode[39-41]. Patterned graphene is integrated in the same physical layer as the metallic resonators, forming a compact monolithic architecture that avoids spacer-based designs[42, 43]. Electrical gating modulates the graphene conductivity and thereby controls the dissipative loss of the qBIC resonance, enabling continuous amplitude modulation of transmitted THz waves. This design provides a balanced trade-off among modulation depth, Q factor, insertion loss, switching speed, and device footprint, offering a scalable framework for active THz modulators.

2. Results and Discussion

2.1 Device structure and operating principle

The architecture of the fully integrated, gate-controlled

active THz modulator is shown schematically in Fig. 1a. The device consists of a periodic DRMA array monolithically integrated with a patterned graphene window that serves as the active gating medium. Because the graphene and metallic DRMA elements are fabricated within the same physical layer, the structure maintains a compact planar geometry and strong near-field coupling. The hybrid graphene-DRMA metasurface is supported by a doped Si substrate and characterized under normal incidence using y-polarized THz radiation. Applying a bias voltage between the back side of the doped Si substrate and the metallic electrode tunes the graphene Fermi level and carrier density, thereby changing the complex conductivity of the atomically thin graphene layer and modulating THz transmission through the device.

The DRMA architecture exploits a qBIC resonance to suppress radiative loss and enhance light-matter interactions at THz frequencies. As shown in Fig. 2(a), an isolated gold rod behaves as a micro-antenna whose resonance frequency is mainly determined by its longitudinal length, but its Q factor is limited by radiative damping. Introducing a second coupled antenna suppresses this radiative loss through the BIC mechanism. The asymmetry of the dimer is controlled by the length difference between the two rods. In the symmetric case,

the structure supports a symmetry-protected BIC that is nearly decoupled from free-space radiation. As the

asymmetry increases, the ideal BIC evolves into a qBIC mode

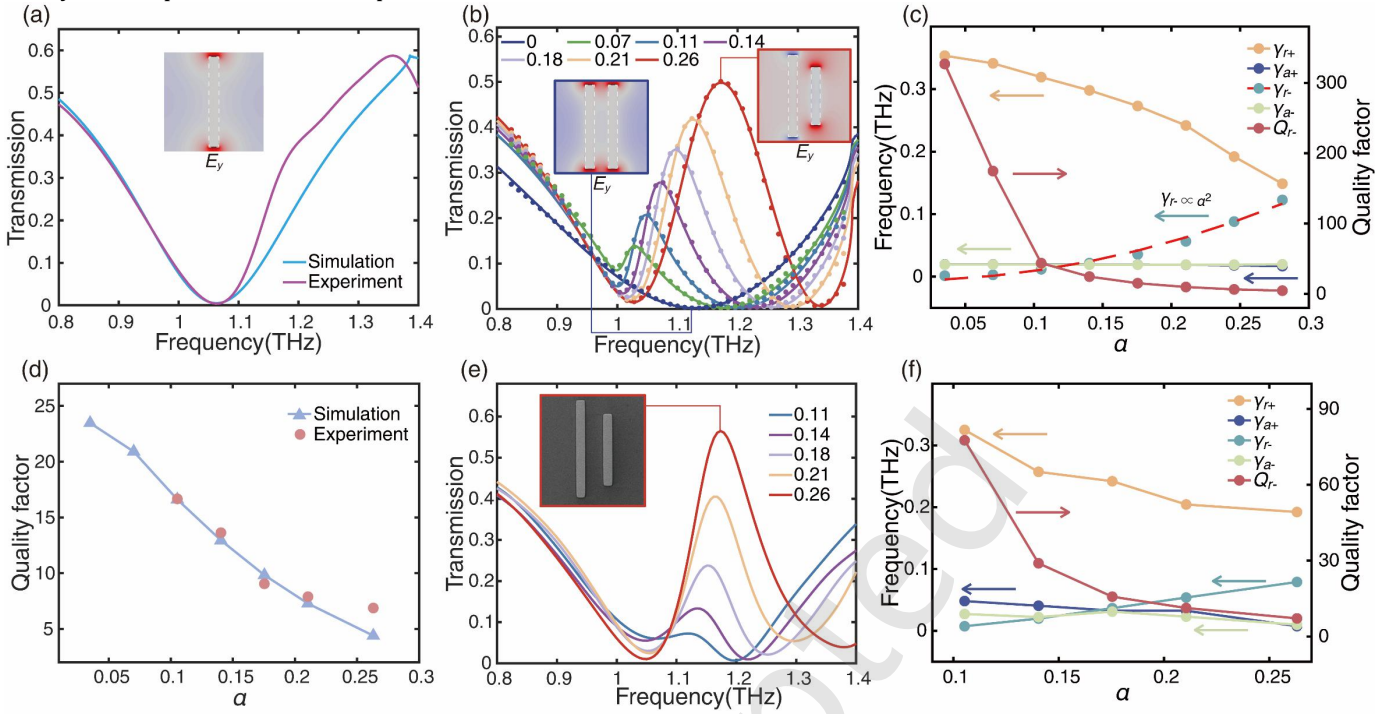


Figure 2. Numerical and experimental characterization of the DRMA qBIC response. (a) Simulated and experimental measured transmission spectra of isolated gold micro-antennas. Inset: E_y distribution at the resonance frequency. (b) Simulated transmission spectra of DRMAs with different asymmetry parameters. The asymmetry parameter is defined as $\alpha = (L_1 - L_2)/L_1$, where L_1 and L_2 denotes the lengths of the two rods, respectively. The analytical fits obtained using the TCMT model (circle) fitted remarkably well with numerical simulations (solid lines). Inset: E_y distribution of the asymmetric qBIC mode. (c) Extracted decay rates and radiative Q factors as a function of structural asymmetry. The red dashed line indicates the characteristic scaling of the symmetry-protected qBIC mode. (d) Comparison between simulated and experimental total Q factors of the DRMAs. (e) Experimentally measured transmission spectra for DRMAs with different asymmetry parameters. Inset: the SEM image of the DRMA with $\alpha = 0.26$. (f) Extracted decay rates from the experimental spectra as a function of structural asymmetry.

with finite radiative coupling. This evolution first produces a Fano resonance superimposed on a low-Q, broad dipolar background, and subsequently gives rise to a high-Q, narrow transparency window whose Q-factor decreases as the radiative coupling to the continuum increases. The calculated near-field distribution in the inset of Fig. 2(b) highlights the asymmetric qBIC modal profile.

Temporal coupled-mode theory (TCMT) was used to describe the electromagnetic response of the DRMA resonator[44]. The system is treated as two coupled resonance modes connected to two external ports:

$$\frac{da}{dt} = jH\mathbf{a} + K^T|s_+\rangle, \#(1)$$

$$|s_-\rangle = C|s_+\rangle + D\mathbf{a}, \#(2)$$

where $\mathbf{a} = [a_1, a_2]^T$ represents the resonance amplitudes within each antenna. The Hamiltonian H is defined as:

$$H = \begin{bmatrix} \omega_1 + j\gamma_1 & \beta \\ \beta & \omega_2 + j\gamma_2 \end{bmatrix}, \#(3)$$

with $\omega_{1,2}$ and $\gamma_{1,2}$ denoting the resonance frequencies and total decay rates of the two resonators, respectively. For a dissipative system, $\gamma_{1,2}$ comprises both absorption and radiative decay rates, i.e., $\gamma_{1,2} = \gamma_{a,1,2} + \gamma_{r,1,2}$. The complex near-field interaction between the antennas is represented by $\beta = \omega_{12} + j\gamma_{12}$. The excitation matrix K and the decay

matrix D characterize the input and output coupling between the resonators and the external ports. Under the constraints of energy conservation and time reversal symmetry, these matrices are equivalent such that $D = K$ [45]. The C matrix accounts for background scattering in the absence of resonators.

Solving Eq. (1) and Eq. (2) yields the relationship between incoming waves $|s_+\rangle$ and outgoing waves $|s_-\rangle$ as $|s_-\rangle = S|s_+\rangle$, where the scattering matrix is given by $S = C - jK(\omega I - H)^{-1}K^T$. Notably, as the two resonators are strongly coupled, hybridized decoupled modes can be derived by diagonalizing the Hamiltonian H :

$$j\omega T^{-1}\mathbf{a} = jH'\mathbf{a} + K'^T|s_+\rangle, \#(4)$$

$$|s_-\rangle = C|s_+\rangle + D'T^{-1}\mathbf{a}, \#(5)$$

In this expression, $T = \sqrt{\frac{1}{(\tilde{\omega}_+ - \tilde{\omega}_2)^2 + \beta^2}} \begin{pmatrix} \tilde{\omega}_+ - \tilde{\omega}_2 & \beta \\ \beta & \tilde{\omega}_- - \tilde{\omega}_1 \end{pmatrix}$ denotes the transformation matrix where $T^{-1} = T^T$. $H' = (T^{-1}HT)T^{-1} = \text{diag}(\tilde{\omega}_+, \tilde{\omega}_-)$ represents the Hamiltonian of the decoupled bright and dark modes. $K' = D' = KT$ denotes the effective excitation and decay matrices, respectively, $T^{-1}\mathbf{a}$ and $\tilde{\omega}_{1,2} = \omega_{1,2} + j\gamma_{1,2}$ represent the eigenvectors and the complex frequencies of the hybridized modes, respectively. The resulting complex eigenvalues $\tilde{\omega}_{\pm}$ are thus

given by:

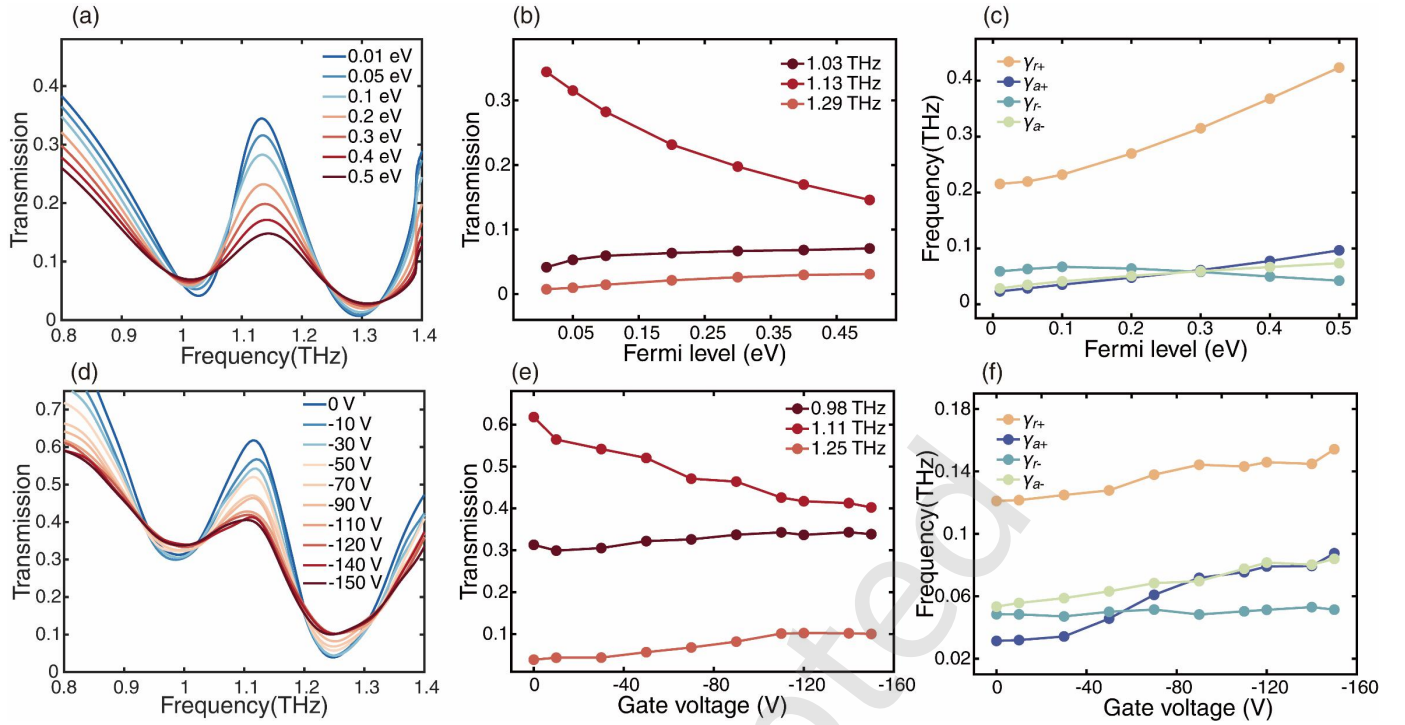


Figure 3. Active THz modulation and TCMT analysis of the hybrid graphene-DRMA modulator. (a-c) Numerical results, including simulated transmittance spectra, transmittance variation at specific frequencies, and TCMT-extracted decay rates for different graphene Fermi levels. (d-f) Experimental results, including measured transmittance spectra, transmittance variation at specific frequencies, and TCMT-extracted decay rates as a function of applied gate voltage.

$$\tilde{\omega}_{\pm} = \frac{\tilde{\omega}_1 + \tilde{\omega}_2}{2} \pm \sqrt{\left(\frac{\tilde{\omega}_1 - \tilde{\omega}_2}{2}\right)^2 + \beta^2}. \#(6)$$

Under the BIC condition where $\tilde{\omega}_1 = \tilde{\omega}_2$, and the excitation coefficients in K matrix satisfy $k_{11} = k_{21}$ and $k_{12} = k_{22}$, the transformation matrix simplifies to $T = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$. Consequently, K' for the hybridized modes is given by:

$$K' = \frac{1}{\sqrt{2}} \begin{bmatrix} k_{11} + k_{12} & k_{21} + k_{22} \\ k_{11} - k_{12} & k_{21} - k_{22} \end{bmatrix}. \#(7)$$

As a result, the radiative coupling rate of the $\tilde{\omega}_-$ modes vanishes such that $\gamma_{r-} = (|k_{11} - k_{12}|^2 + |k_{21} - k_{22}|^2)/2 = 0$. For qBIC states, γ_{r-} remains a small but nonzero value, which is strictly governed by the structural asymmetry.

To validate this theoretical description, the simulated spectra for different asymmetry parameters were fitted using the TCMT model, as shown by the red dashed lines in Fig. 2(b). The fitting results agree well with the full-wave simulations. The extracted radiative decay rates and corresponding radiative Q factors of the qBIC mode are plotted in Fig. 2(c). As expected for symmetry-protected states, the dark qBIC mode follows the characteristic inverse-square scaling with structural asymmetry[39]. The extracted total Q factors for qBIC modes are summarized in Fig. 2(d). Although the total Q factor is reduced by intrinsic ohmic loss in the gold resonators, the DRMA architecture still maintains a relatively high Q factor compared with many THz modulation approaches. A similar trend is

observed experimentally in the fabricated DRMAs (Fig. S1 in the Supplementary Information), where THz time-domain spectroscopy (THz-TDS) measurements, TCMT fits, and extracted decay rates are shown in Fig. 2(e) and Fig. 2(f).

When patterned graphene is integrated with the DRMA, the qBIC resonance can be actively modulated through electrostatic carrier injection. The qBIC mode interacts with graphene through its highly confined, subwavelength near-field. When the DRMA supports a high-Q qBIC resonance, the electric field is substantially enhanced and extends evanescently into the graphene layer. This evanescent field drives surface currents in the graphene, and the resulting Ohmic dissipation acts back on the resonator as an additional non-radiative loss channel. We note that the patterned graphene window plays a critical role in maintaining the high-Q qBIC mode. As shown in Fig. S2, the patterned-graphene device is compared with an otherwise identical structure employing a continuous, unpatterned monolayer graphene. The corresponding transmission spectra are compared in Figs. S2(c) and S2(d). With the patterned graphene, a sharp, high-Q transmission peak emerges near 1.25 THz, corresponding to the qBIC mode. In stark contrast, the device with the unpatterned graphene layer exhibits no distinct resonant feature in the same spectral window, and the qBIC mode is almost completely suppressed. We attribute this quenching to the severe Ohmic loss introduced by the continuous graphene layer, which overdamps the resonant mode. The patterned-graphene approach preserves the intrinsic dynamic tunability of graphene while drastically suppressing parasitic absorption, thereby enabling the qBIC mode to retain a high Q-factor

suitable for efficient electrically controlled modulation.

In the simulations, graphene was modeled as a two-dimensional surface current using the Kubo formalism. In the THz regime, the graphene conductivity is dominated by intraband transitions and can be approximated by a Drude-like response[46-48]:

$$\sigma(\omega) = \frac{ie^2 E_F}{\pi \hbar^2 (\omega + i\tau^{-1})}, \#(8)$$

where e is the charge of the electron and τ denotes the DC relaxation time. The applied gate voltage induces a change in the carrier density which consequently shifts the Fermi level E_F , according to the relationship $E_F = \hbar v_F \sqrt{\pi N}$. Here, v_F represents the Fermi velocity and N is the total carrier density defined as $N = \sqrt{n_0^2 + \eta^2 |\Delta V|^2}$, where n_0 is the residual carrier concentration arising from density fluctuations near the Dirac point and η denotes the gate capacitance of the dielectric oxide layer.

Consequently, the qBIC effectively senses the graphene as a frequency dependent complex conductivity, whose value is controlled by the gate voltage. Fig. S3 depicts the electric field distribution, induced current distribution and power dissipation within the DRMA modulator at resonance frequencies. At low Fermi levels, the patterned graphene behaves mainly as a weakly absorbing dielectric layer. As the Fermi level increases under electrostatic gating, the graphene conductivity rises and introduces controllable

dissipative loss into the qBIC resonator. As shown in Fig. 3(a), the resonance frequency remains nearly unchanged over the tuning range, whereas the narrow transparency window is gradually suppressed by the increased loss.

The mechanism is further confirmed by extracting the absorption rates with the TCMT framework. In the presence of graphene, the absorption decay rate of each resonator acquires an additional channel:

$$\gamma'_{a1,2} = \gamma_{a1,2} + \gamma_g(E_F), \#(9)$$

where $\gamma_g(E_F)$ is the graphene-induced loss, which scales with graphene conductivity $\Re(\sigma(E_F))$. Diagonalizing the Hamiltonian H yields the decay rates of the hybridized qBIC modes, $\gamma'_{\pm} = \gamma_{\pm} + \gamma_{g\pm}(E_F)$. Under electrical gating, $\gamma_{g\pm}$ increases as the Fermi level departs from the charge neutrality point, providing a controllable dissipative damping channel. This mechanism enables efficient transmittance modulation, yielding a simulated modulation depth approaching 57% as the Fermi level increases from 0.01 eV to 0.5 eV (Fig. 3(b)). From the TCMT fits, we extract power-law dependences of the decay channels on E_F (Fig. 3(c)), $\gamma_{a+} \propto E_F^{1.22}$, $\gamma_{a-} \propto E_F^{0.69}$, confirming that the absorptive loss is strongly modulated. For the dark qBIC mode, the radiative decay rate remains nearly constant, while the absorption rate increases from 0.12 to 0.3 meV, directly suppressing the resonant transparency.

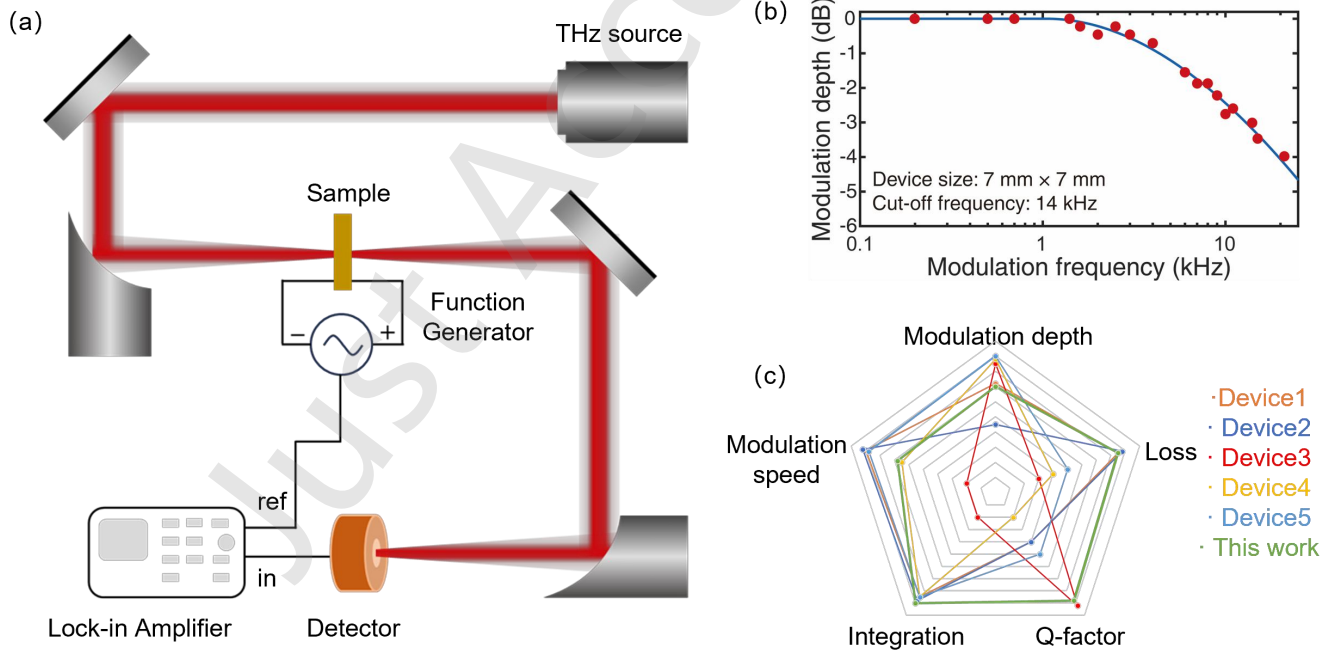


Figure 4. Modulation speed and performance comparison. (a) Schematic of the experimental setup for THz modulation-speed measurements. (b) Normalized modulation depth as a function of modulation frequency. (c) Performance comparison with representative THz modulators in terms of modulation depth, modulation speed, Q factor, integration, and loss[20, 33, 50, 51, 61].

2.2 Device fabrication and modulation performance

We experimentally validated the performance of the graphene-DRMA platform using a back-gated device configuration. Figure 1(c) shows an optical micrograph of a representative modulator, and Fig. 3(d) presents the gate-dependent transmission spectra as the applied voltage was swept from 0 to -150 V. Transmission spectra for additional

modulators with different asymmetry parameters are provided in Fig. S4 – S6 and Table S1. The experimental spectra agree well with the numerical simulations. Consistent with previously reported CVD-grown graphene[49], the device exhibits slight p-doping, likely caused by residual adsorbates introduced during transfer and fabrication. As a result, the charge-neutrality point (CNP) appears at a positive gate voltage. At the CNP, dissipative

loss from graphene is minimized, yielding a maximum transmittance of 61.9% at 1.1 THz and a measured Q factor of 9.28. As the gate voltage is decreased from 0 to -150 V, the transmittance at this frequency falls from 61.9% to 40.2%. The modulation depth (MD), defined as $MD = (T_{max} - T_{min}) / T_{max}$, is determined to be 35.0%, where T_{max} and T_{min} denote the maximum and minimum transmittance during modulation, respectively. The absolute modulation depth (AMD), defined as $AMD = T_{max} - T_{min}$, quantifies the raw transmittance contrast between the ON and OFF states and reaches 22%. The MD values of three additional devices reach 28.3%, 33.0%, and 18.3% (Fig. S4(d), Fig. S5(d) and Fig. S6(d)), respectively. TCMT fitting of the experimental spectra (Fig. 3(f)) shows that the absorption rate of the dark qBIC mode increases from 0.22 to 0.34 meV during carrier injection, in agreement with the proposed loss-modulation mechanism. The slightly larger loss compared with the numerical prediction is attributed primarily to carrier scattering and residual contamination introduced during graphene transfer and lithographic processing.

The DRMA architecture features a higher Q-factor than the conventional micro-antenna and consequently provides a larger absolute modulation depth and lower resonant loss. For the device with $\alpha = 0.21$, the qBIC mode achieves an absolute modulation depth of 21.8% at 1.11 THz, whereas the conventional dipolar antenna mode achieves only 6.3% at 1.25 THz. Across all fabricated devices (Fig. 3 and Figs. S4–S6 in the Supplementary Information), the qBIC resonance consistently shows a much stronger gate-induced transmission change and lower insertion loss than the broad dipolar background. Moreover, when the graphene conductivity increases sufficiently, the narrow qBIC resonance near 1.1 THz is almost completely quenched, while the dipole mode only broadens without a significant lineshape change. This further demonstrates that the DRMA architecture is considerably more sensitive to external perturbations and is therefore better suited for efficient amplitude modulation than the conventional micro-antenna.

The modulation speed of the hybrid graphene-DRMA modulator was also characterized. As illustrated in Fig. 4(a), a continuous-wave THz laser was used as the radiation source, a function generator supplied the modulation voltage, and a high-speed THz detector recorded the modulated signal. The signal was processed with a lock-in amplifier, and the modulation depth at each frequency was normalized to the value measured at 334 Hz. As shown in Fig. 4(b), the measured 3 dB cutoff frequency is approximately 14 kHz. This speed is mainly limited by the RC constant of the present back-gated architecture, where the capacitance is dominated by the large graphene active area and the resistance arises mainly from the graphene sheet. Using the device geometry, the calculated 3 dB bandwidth is 13.94 kHz (Materials and Methods), in good agreement with the experiment. Importantly, this bandwidth is not an intrinsic limit of the graphene-qBIC platform and can be further improved by reducing the active area, using thinner high-k gate dielectrics, or adopting a top-gate configuration.

2.3 Performance comparison and outlook

The device performance is summarized and compared with representative graphene-based THz modulators in Fig. 4(c). The present monolithic graphene-DRMA modulator achieves a modulation depth of 35% at 1.1 THz while maintaining a Q factor of 9.28, a spectral bandwidth of 0.12 THz, a 3 dB modulation speed of 14.0 kHz, and an insertion loss of 2.08 dB. In addition, the device requires a gate-voltage swing of approximately 150 V, which is comparable to values reported for back-gated graphene modulators employing relatively thick SiO₂ gate dielectrics. Rather than optimizing a single metric at the expense of others, this architecture provides a balanced combination of resonance quality, modulation depth, loss, integration, and switching speed. When compared against unstructured graphene modulators (Table 1), our patterned design demonstrates superior resonance quality and lower dissipative loss while maintaining a compact footprint.

Table 1 Comparison of typical electrically controlled graphene-based THz amplitude modulators

Device design	Frequency (THz)	Modulation depth	Absolute modulation depth	Modulation speed	Loss	Q_factor	Thickness	Operating voltage	Ref.
	1.5 ~ 5	38%	20%	N/A	2.4 dB	N/A	12.8 μ m	-0.3 V to +0.6 V	[55]
	0.1 ~ 2.5	99%	N/A	N/A	5.7 dB	N/A	50 μ m	3 V	[56]
Unstructured graphene, liquid ion gel gate	0.31	35 dB	N/A	N/A	N/A	<3 (estimated)	85 μ m	2 V	[57]
	0.582	70%	39%	N/A	2.15 dB	14	207 μ m	-25 V to +25 V	[32]
	0.75	30%	15%	N/A	3 dB	<7 (estimated)	5 μ m	1.7 V	[29]
Unstructured graphene, all	0.57	15%	N/A	20 kHz	N/A	N/A	Single atomic	50 V	[24]

solid-state structure							layer		
	0.4 ~ 1.5	12.8%	N\A	N\A	N\A	N\A	Single atomic layer	-20 V to +45 V	[58]
	0.5 ~ 1.6	99.90%	<0.063%	10 kHz	12 dB	N\A	Single atomic layer	-12 V to +12 V	[20]
	2.68	90 %	<10%	20 kHz	11 dB	<3 (estimated)	14 μ m	10 V	[54]
Unstructured graphene, metal metamaterial	0.4	50%	<12.5%	N\A	6 dB	1.5	100 nm	-20 V to +20 V	[59]
	0.6	20.35%	11.5%	N\A	4 dB	4	200 nm	-10.6 V to +3.4 V	[60]
	0.2	16 dB	~1.545%	N\A	~18 dB	19	254 μ m	6 V	[33]
	2	4%	N\A	105 MHz	N\A	<3 (estimated)	75 nm	120 V	[61]
	0.75	7.6 dB	3.69%	3 GHz	13.5 dB	<3 (estimated)	150 nm	-120 V to +120 V	[52]
Patterned graphene, metamaterial	2.15	40.1 dB	~10%	30 MHz	10 dB	N\A	170 nm	-80 V to +180 V	[51]
	0.47	8.4 dB	~1.13%	N\A	18 dB	<4 (estimated)	200 nm	90 V	[62]
	4.6	40%	25%	41 MHz	2 dB	~2	85 nm	-120 V to +15 V	[50]
	2.24	32%	8%	5 MHz	6 dB	<7 (estimated)	80 nm	-100 V to +25 V	[63]
	1.6	33%	14%	N\A	3.77 dB	N\A	110 nm	-125 V to +50 V	[30]
Patterned graphene, qBIC	1.1	35%	22%	14 kHz	2.08 dB	9.28	100 nm	-150 V	This work

Furthermore, as listed in Table 1, many existing modulators exhibit a high MD but poor AMD owing to substantial terahertz loss. Benefiting from suppressed insertion loss and a remarkable AMD, our proposed graphene-based qBIC THz modulator is well suited for use with low-power terahertz sources. In addition, in contrast to previous metamaterial-based modulators which often exhibit either high insertion loss or relatively low modulation depths, our platform achieves a synergistic balance of performance metrics (Table 1). The operating voltage remains relatively high because of the 300 nm SiO₂ gate dielectric and the limited efficiency of the back-gating configuration. Replacing SiO₂ with high-k dielectrics[53] such as HfO₂ or Al₂O₃, or adopting a top-gate design[54], should reduce the required voltage without substantially increasing device thickness or compromising integration.

Additionally, the modulator performance can be further

improved through several strategies. The Q factor can be enhanced by improving lithographic precision, optimizing the metal deposition process, or adopting more robust qBIC configurations, such as Brillouin-zone-folded qBICs[64]. Although the functional stack is already approximately 100 nm thick and difficult to reduce further in the vertical direction, the lateral footprint can be readily reduced by minimizing the graphene area.

The modulation depth can be further enhanced by improving graphene quality and carrier transport. Dry-transfer techniques can suppress surface wrinkles and organic residues, thereby increasing carrier mobility and widening the accessible conductance range[65]. For electrically controlled terahertz devices, the modulation performance can also be improved by encapsulating graphene with hexagonal boron nitride[66] or by adopting a top-gate configuration[67]. Finally, reducing the active area

or employing thinner high-k gate dielectric layers is expected to improve the modulation speed of the proposed device.

3. Conclusion

In conclusion, we have demonstrated a monolithic graphene-qBIC THz modulator that combines patterned graphene with symmetry-broken double-rod resonators. The qBIC resonance suppresses radiative loss and enhances the interaction between THz waves and electrically tunable graphene, while electrostatic gating controls the dissipative loss of the resonance and enables continuous amplitude modulation. The fabricated device achieves a modulation depth of 35%, a Q factor of 9.28, a spectral bandwidth of 0.12 THz at 1.1 THz, a 3 dB modulation speed of 14 kHz, and an insertion loss of 2.08 dB. The monolithic design offers a compact and practical route for balancing modulation depth, resonance quality, insertion loss, switching speed, and device integration. These results establish qBIC-enhanced graphene metasurfaces as a promising platform for active THz photonic devices, with further opportunities for improved speed and lower operating voltage through device scaling and advanced gate architectures.

4. Materials and Methods

Numerical simulation: Transmission spectra and near-field electric-field distributions of the designed micro/nano-resonators were calculated using COMSOL Multiphysics. The complex dielectric function of gold was described using a Drude-Lorentz model with a plasma frequency of $1.38 \times 10^{16} \text{ rad s}^{-1}$ and a collision frequency of $1.07527 \times 10^{14} \text{ rad s}^{-1}$. The refractive indices of Si and SiO₂ were set to 3.42 and 1.955, respectively. The monolayer graphene sheet was modeled as a two-dimensional surface current using the Drude model. The relaxation time of graphene is set to 50 fs [68] in all full-wave simulation files. The geometric parameters of the designed unit cell were $P = 63 \text{ } \mu\text{m}$, $L_1 = 57 \text{ } \mu\text{m}$, $W = 6 \text{ } \mu\text{m}$, $G = 10 \text{ } \mu\text{m}$, and $g = 2 \text{ } \mu\text{m}$.

Device fabrication and characterization: The devices were fabricated on 500 μm thick double-side-polished p-doped Si substrates ($\sim 10 \text{ } \Omega \text{ cm}$) with a 300 nm SiO₂ layer. Large-area CVD-grown monolayer graphene (Jiangsu XFNANO Materials Tech. Co., Ltd.) was transferred onto the substrate using a standard wet-transfer process. The graphene pattern was defined by ultraviolet maskless photolithography (TuoTuo Technology, UV Litho-ACA) followed by O₂ plasma etching. The metal resonators and electrodes were then defined by a second photolithography step, thermal evaporation of Cr/Au (10/90 nm), and lift-off. The thickness of Cr/Au stack was chosen to balance optical performance, ohmic loss, fabrication reliability, and integration compatibility (Fig. S8). Silver paste was applied to the back side of the substrate to form the back-gate electrode. Electrical properties were measured using a Keithley 2636B source meter. Raman spectra of graphene were acquired using a Renishaw InVia Reflex confocal Raman spectrometer. The Raman spectrum and electrical characterization of graphene are shown in Fig S9 and Fig S10, the major Raman features of transferred graphene match well with the results in reference[69].

THz-TDS measurements: Transmission spectra were measured using a THz time-domain spectrometer (BATOP,

TDS-1008) under ambient conditions. During modulation-depth measurements, a source meter was used as a DC power supply with a maximum output voltage of 200 V. To avoid Fabry-Perot interference from the Si substrate, the first temporal transmission peak was extracted to obtain the frequency-domain spectrum.

Modulation-speed measurement: The modulation speed is limited by the resistance-capacitance (RC) time constant of the device. The capacitance originates from the back-gate structure, where the 300 nm SiO₂ dielectric layer sandwiched between graphene and the silicon substrate forms a parallel-plate capacitor. With an active device area of $7 \times 7 \text{ mm}^2$ and a relative permittivity $\epsilon_r = 3.95$ for SiO₂, the geometric capacitance is

$$C = \frac{\epsilon_0 \epsilon_r A}{d} = 5.71 \text{ nF.} \#(10)$$

The resistance is dominated by the graphene sheet, whose measured sheet resistance is approximately 2000 Ω , and contact resistances are negligible in this back-gated geometry. The external circuit contributes a 50 Ω source resistance, and the substrate resistance of the 500 μm thick doped Si wafer is estimated to be on the order of a few ohms; both are negligible compared with the graphene resistance. The resulting 3 dB cutoff frequency is therefore

$$f_{3\text{dB}} = \frac{1}{2\pi RC} = 13.94 \text{ kHz.} \#(11)$$

The modulation-speed measurement was performed using a gas laser (Edinburgh, FIRL100) with formic acid as the far-infrared lasing medium. A function generator (RIGOL, DG4062) provided a 10 V peak-to-peak square-wave modulation signal. The modulated THz signal was detected using an antenna-coupled HEMT THz detector equipped with a silicon lens and then fed into a lock-in amplifier (Stanford Research Systems, SR560). The modulation depth at each frequency was normalized to the value measured at 334 Hz, a typical modulation frequency used for mechanical choppers.

Reproducibility and uniformity of the devices: The authors fabricated 20 samples in total, yielding 14 working devices and a fabrication success rate of 70%. Four representative modulators are presented in the manuscript and Supporting Information; their consistent experimental behavior agrees well with the simulations and confirms the reproducibility of the fabrication process. Measurements of metallic metasurfaces with the same geometric parameters show nearly identical resonant frequencies, demonstrating excellent reproducibility of the metallic resonator arrays. Device-to-device variations in modulation performance arise mainly from differences in graphene patterning and from spatial nonuniformities in the CVD-grown graphene, such as doping inhomogeneity and lattice defects. Further improvements in CVD graphene quality are therefore desirable to ensure fully reproducible gate-controlled graphene-based metamaterials.

The main cause of device failure is electrical breakdown associated with the large lateral dimensions and the high back-gate operating voltage. Intrinsic pinholes in the oxide layer and fabrication-induced damage to the dielectric film can collectively lead to breakdown. As discussed in the main text, adopting a top-gate configuration, replacing the SiO₂

layer with high-k dielectrics, or reducing the graphene coverage area could substantially improve device yield and reproducibility.

The device uniformity is also evaluated by repeating THz-TDS measurements on the same sample on different days with different sample alignment configurations. The THz beam diameter is approximately 1 cm, which fully covers the device active area. Therefore, the spatial nonuniformity of the graphene layer does not significantly degrade the measured modulation uniformity. For the device with an asymmetry factor $\alpha = 0.18$, two independent measurements yielded modulation depths of 21.78% and 22.52%, confirming the reliable uniformity of the fabricated device.

Electronic Supplementary Material: Supplementary material (extracted results and fitting results of decay rates and radiative Q factors as a function of structural asymmetry, comparison of proposed qBIC device with unpatterned/patterned graphene, simulated electromagnetic response of the graphene-DRMA modulator, active THz modulation and TCMT analysis of the hybrid graphene-DRMA modulator with $\alpha=0.26$, 0.18, and 0.14, modulation depth of various THz modulators at different operating bands, broadband experimental transmittance spectra of THz modulators, comparison of the proposed qBIC device with different metal thicknesses, Raman spectrum of graphene, electrical characterization of graphene in THz modulator) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94909177>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and/or the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

Haili Yang: Writing manuscript, experimental design, data curation
Ningsheng Xu: Initiate study, project administration, writing manuscript
Wuchao Huang: Methodology, experimental design
Shangdong Li: Methodology, investigation
Ximiao Wang: Methodology, investigation
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Huanjun Chen: Initiate study, project administration, writing manuscript, funding acquisition

Shaozhi Deng: Initiate study, project administration, writing manuscript, funding acquisition

All the authors have approved the final manuscript.

Use of AI statement

None.

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Electronic Supplementary Material

Monolithic graphene–qBIC resonators for electrically tunable terahertz modulation

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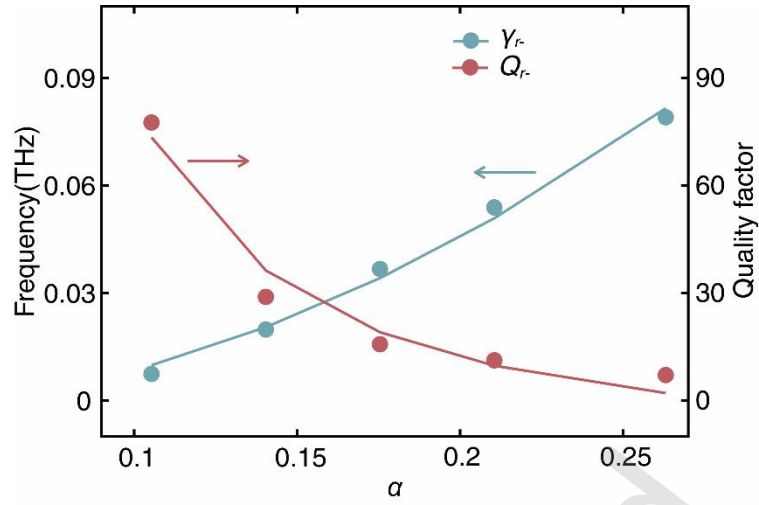


Figure S1. Extracted results (circle) and fitting results (solid line) of decay rates and radiative Q factors as a function of structural asymmetry.

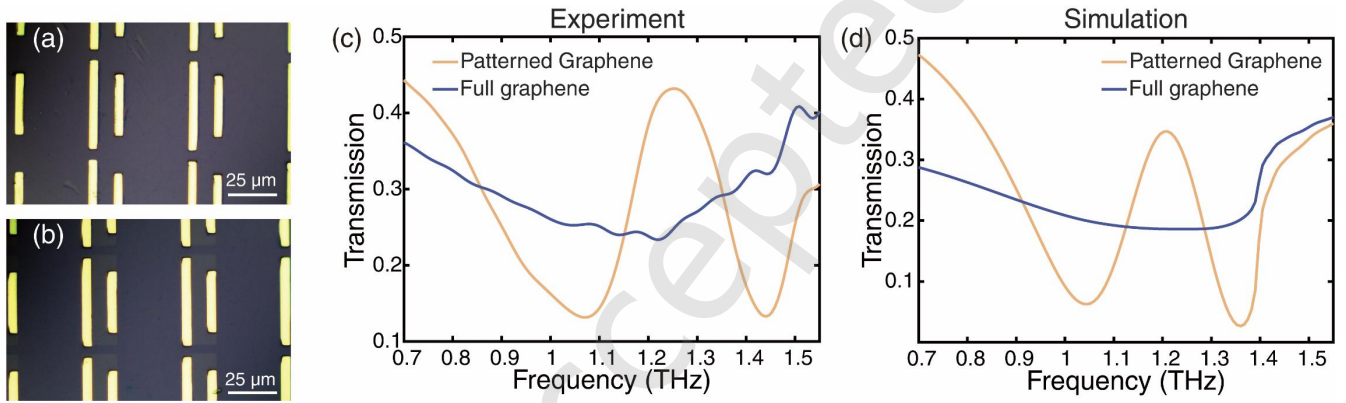


Figure S2. Comparison of proposed qBIC device with unpatterned/patterned graphene. (a-b) Top-view optical micrograph of qBIC device with (a) unpatterned and (b) patterned graphene. (c-d) Experimental and simulated transmittance spectra of proposed device. With the patterned graphene, a sharp, high- Q transmission peak emerges near 1.25 THz, which is the qBIC mode described in the manuscript. In stark contrast, the device with the unpatterned graphene layer exhibits no distinct resonant feature in the same spectral window. And the qBIC mode is almost completely suppressed.

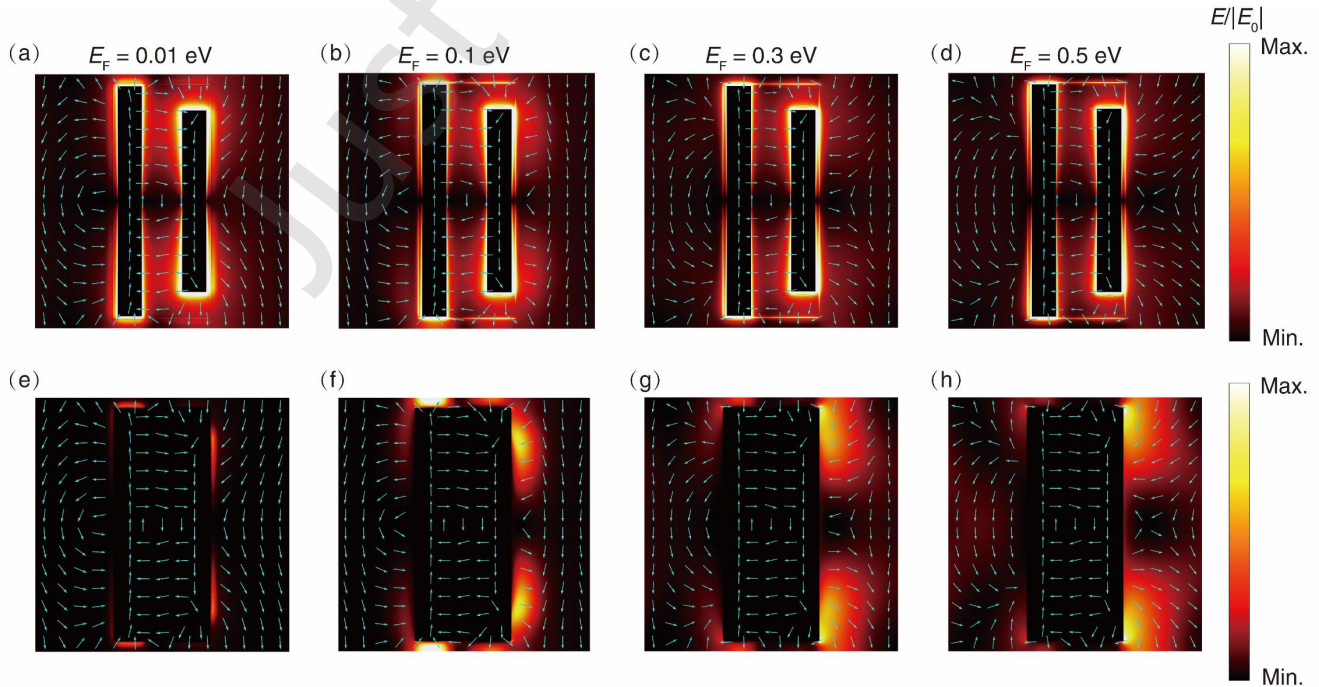


Figure S3. Simulated electromagnetic response of the graphene-DRMA modulator at 1.13 THz. (a-d) Normalized electric field magnitude $|E|/|E_0|$ for graphene Fermi levels of (a) 0.01 eV, (b) 0.1 eV, (c) 0.3 eV, and (d) 0.5 eV, where E_0 is the incident electric field. (e-h) Corresponding normalized power

dissipation density $Q_{loss} = \frac{1}{2} \Re(\sigma \mathbf{E} \cdot \mathbf{E}^*)$ for the same Fermi levels. In (e-h), dissipation within the metal rods is masked for clarity. Cyan arrows indicate the induced surface current density $\mathbf{J}$. At a low Fermi level ($E_F=0.01$ eV), graphene behaves essentially as a dielectric with negligible loss; the qBIC field is strongly localized, but the dissipation remains very low. As E_F increases, the field profile of the qBIC mode is only weakly perturbed, whereas the power dissipation grows dramatically. This unambiguously shows that electrical gating primarily introduces a tunable dissipative loss, rather than substantially reshaping the resonant mode.

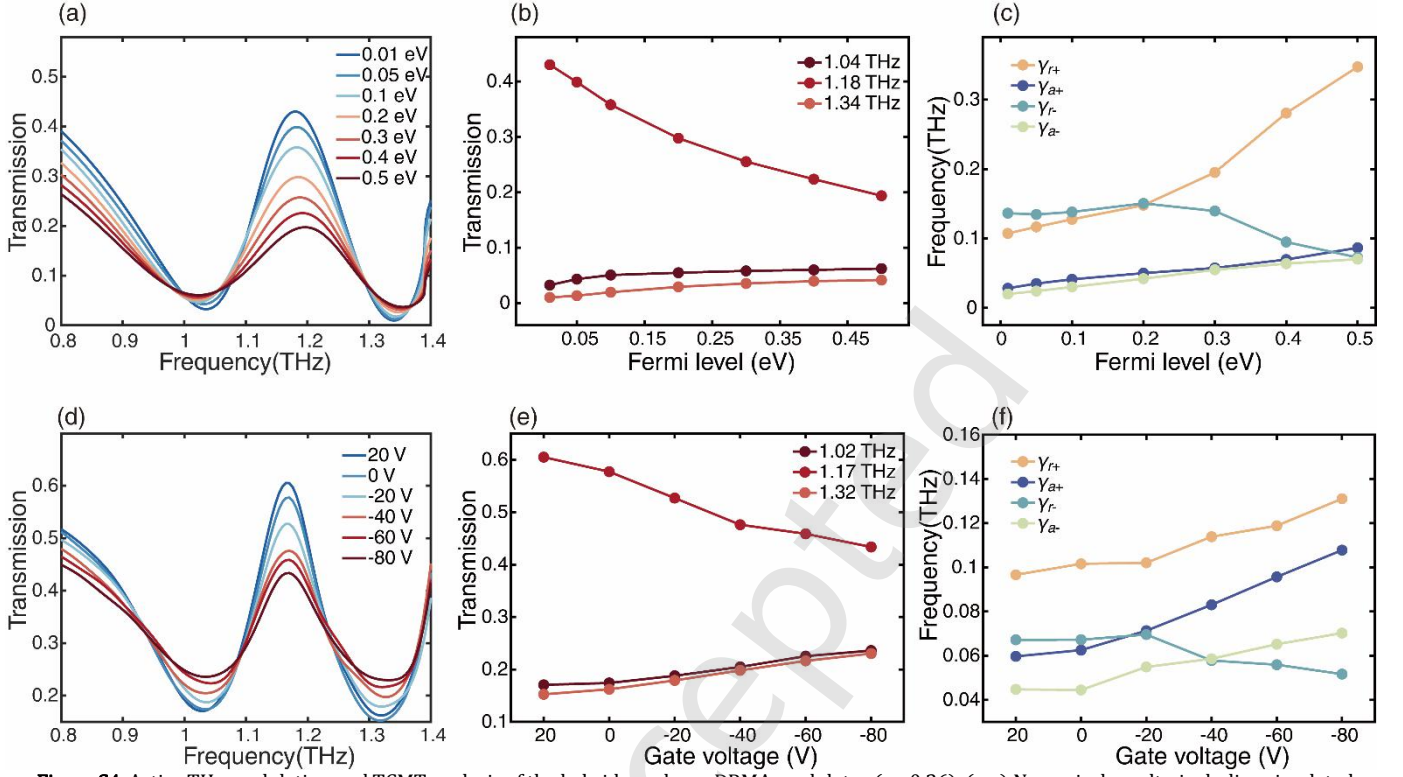


Figure S4. Active THz modulation and TCMT analysis of the hybrid graphene-DRMA modulator ($\alpha=0.26$). (a-c) Numerical results, including simulated transmittance spectra, transmittance variation at specific frequencies, and TCMT-extracted decay rates for different graphene Fermi levels. (d-f) Experimental results, including measured transmittance spectra, transmittance variation at specific frequencies, and TCMT-extracted decay rates as a function of applied gate voltage.

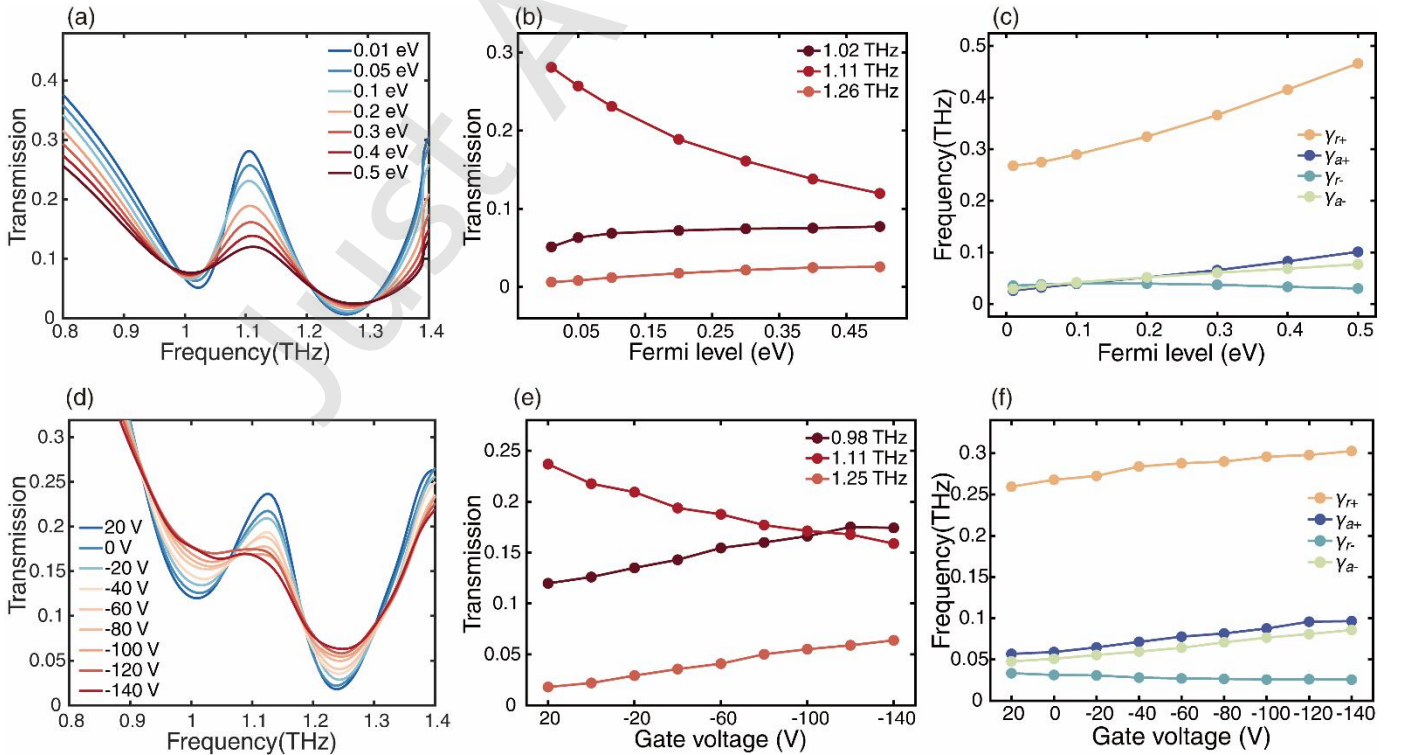


Figure S5. Active THz modulation and TCMT analysis of the hybrid graphene-DRMA modulator ($\alpha=0.18$). (a-c) Numerical results, including simulated transmittance spectra, transmittance variation at specific frequencies, and TCMT-extracted decay rates for different graphene Fermi levels. (d-f) Experimental results, including measured transmittance spectra, transmittance variation at specific frequencies, and TCMT-extracted decay rates as a function of applied gate voltage.

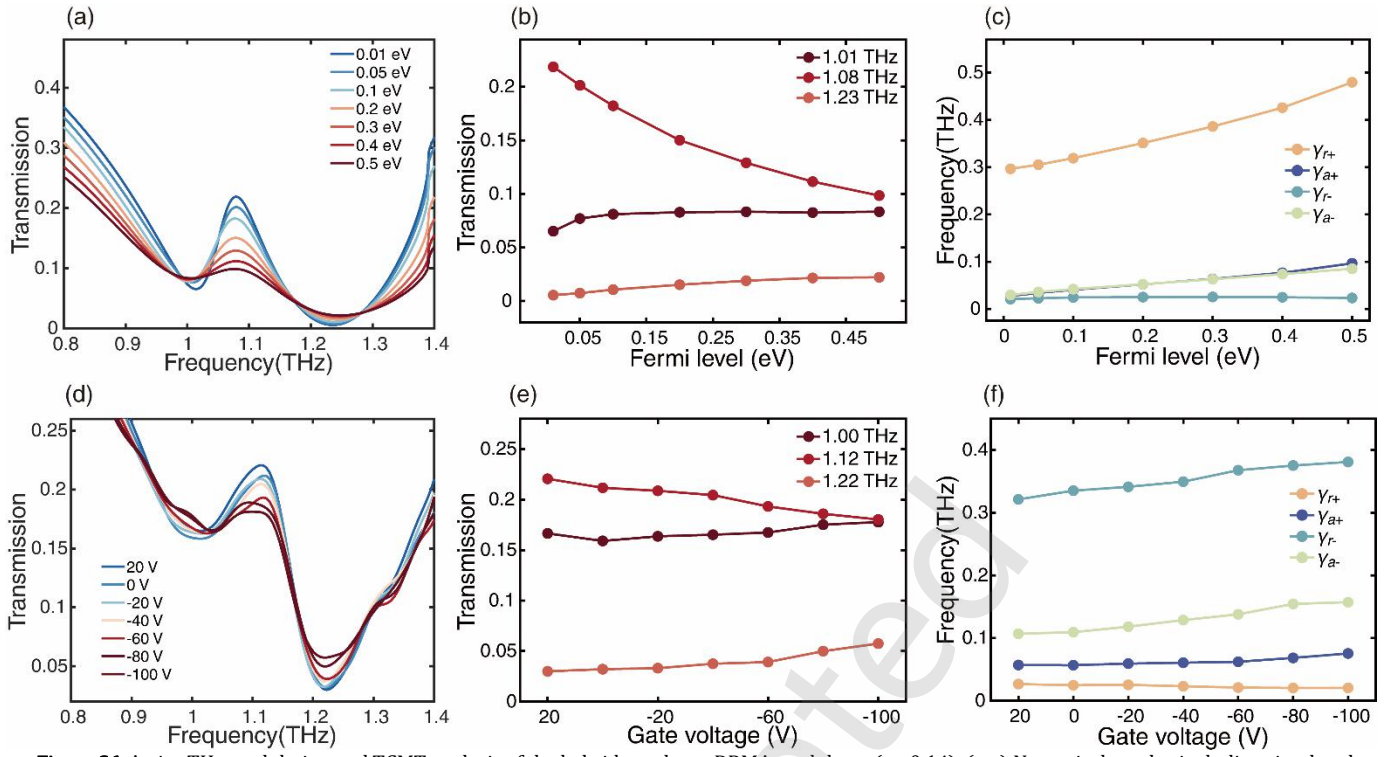


Figure S6. Active THz modulation and TCMT analysis of the hybrid graphene-DRMA modulator ($\alpha=0.14$). (a-c) Numerical results, including simulated transmittance spectra, transmittance variation at specific frequencies, and TCMT-extracted decay rates for different graphene Fermi levels. (d-f) Experimental results, including measured transmittance spectra, transmittance variation at specific frequencies, and TCMT-extracted decay rates as a function of applied gate voltage.

Table S1. Modulation depth and absolute modulation depth of various THz modulators at different operating bands.

α	0.26			0.21			0.18			0.14		
Freq (THz)	1.02	1.17	1.32	0.98	1.11	1.25	1.01	1.13	1.24	1.00	1.12	1.22
MD	27.7 %	28.3 %	33.8 %	11.6 %	35.0 %	61.2 %	31.6 %	33.0 %	71.8 %	10.5 %	18.3 %	47.8 %
AMD	6.8%	17.2 %	7.7%	4.8%	21.8 %	6.3%	5.6%	7.8%	4.6%	2.1%	4.1%	2.9%

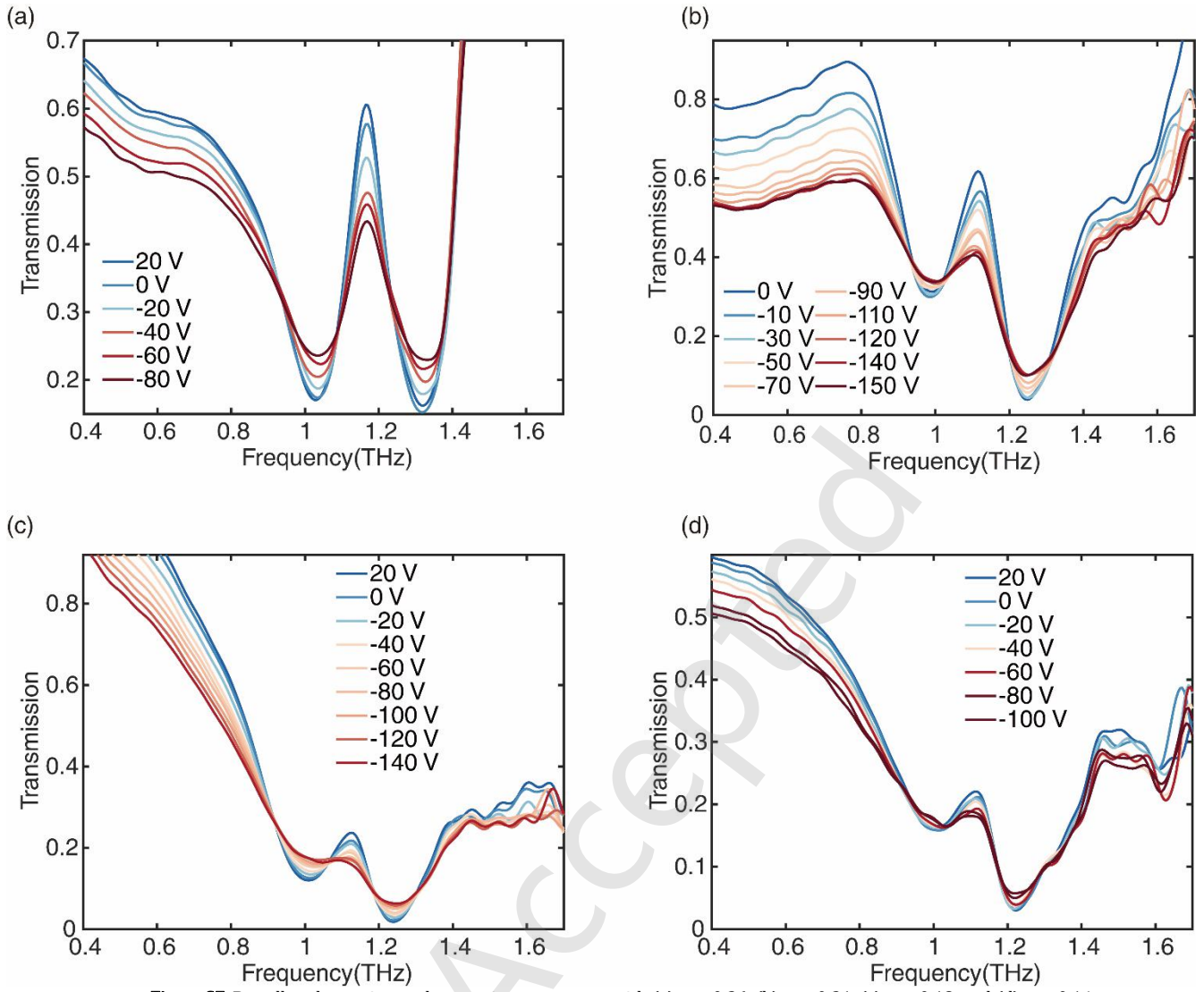


Figure S7. Broadband experimental transmittance spectra with (a) $\alpha = 0.26$, (b) $\alpha = 0.21$, (c) $\alpha = 0.18$, and (d) $\alpha = 0.14$.

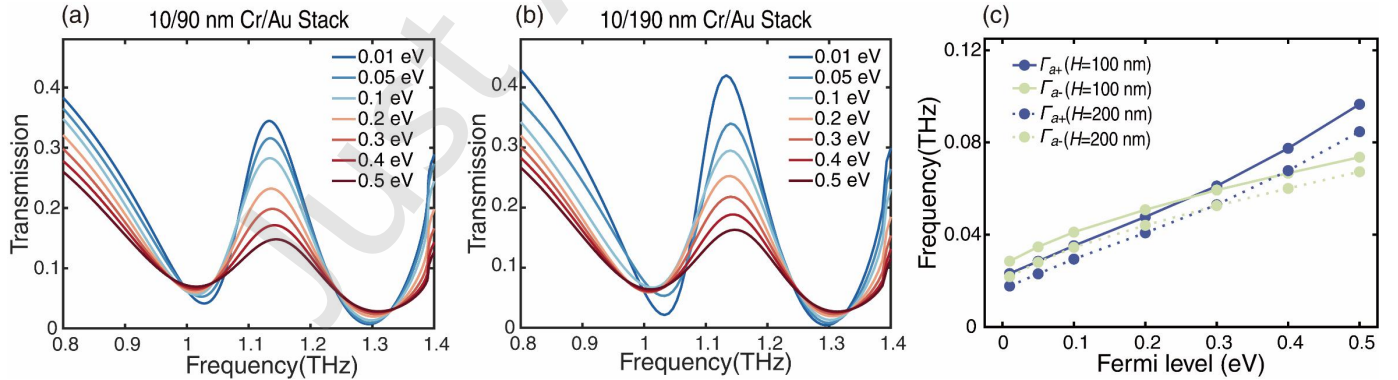


Figure S8. Comparison of the proposed qBIC device with different metal thicknesses. (a–b) Simulated transmission spectra for Cr/Au layer thicknesses of (a) 10/90 nm and (b) 10/190 nm at different graphene Fermi levels. (c) Comparison of the TCMT-extracted absorption rates as a function of graphene Fermi level for the two configurations. With the increased metal thickness, the modulation depth increases modestly from 56.3% to 61.2%, while the absorption rates of the hybridized modes $\tilde{\omega}_{\pm}$ decrease by only 7 GHz on average. The Q-factor improves by about 0.7, indicating that once the Au thickness already exceeds the skin depth, further thickening only slightly suppresses metal absorption. From a fabrication perspective, increasing the Au thickness to 200 nm would extend the thermal evaporation process, make lift-off more difficult, and increase the risk of surface roughness and residual stress. Our deposition system produces uniform 90 nm Au films at 0.4–0.5 Å/s, yielding reliable and reproducible metasurfaces. We therefore selected the 10/90 nm Cr/Au stack as a practical compromise between electromagnetic performance and fabrication robustness.

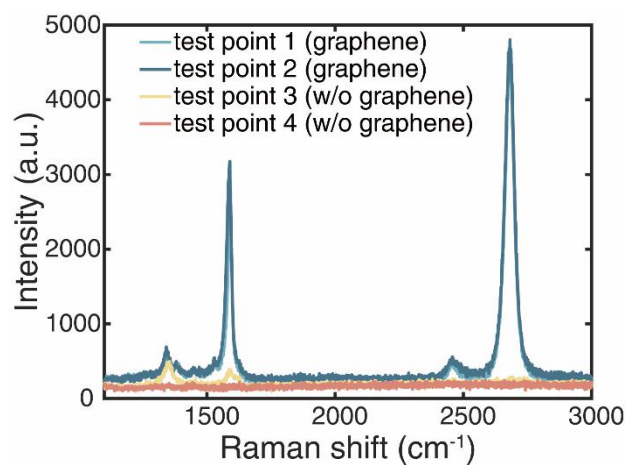


Figure S9. Raman spectrum of graphene using 532 nm laser as excitation.

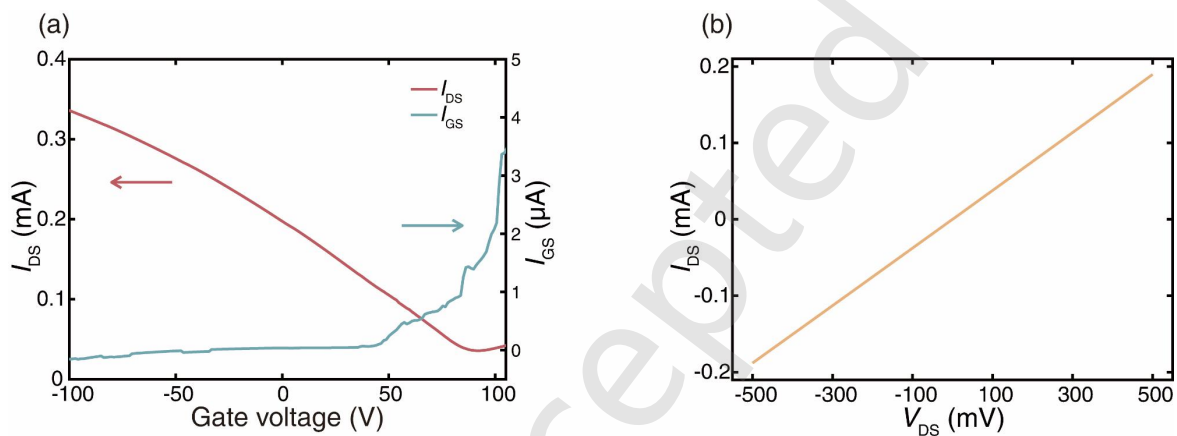


Figure S10. Electrical characterization of graphene in THz modulator. (a) Transfer characteristic curves. (b) I-V characteristics.