Highly Sensitive and Wide-Band Tunable Terahertz Response of Plasma Waves Based on Graphene Field Effect Transistors

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Terahertz (THz) technology is becoming a spotlight of scientific interest due to its promising myriad applications including imaging, spectroscopy, industry control and communication. However, one of the major bottlenecks for advancing this field is due to lack of well-developed solid-state sources and detectors operating at THz gap which serves to mark the boundary between electronics and photonics. Here, we demonstrate exceptionally wide tunable terahertz plasma-wave excitation can be realized in the channel of micrometer-level graphene field effect transistors (FET). Owing to the intrinsic high propagation velocity of plasma waves (\(c_v \approx 10^8\) cm/s) and Dirac band structure, the plasma-wave graphene-FETs yield promising prospects for fast sensing, THz detection, etc. The results indicate that the multiple guide-wave resonances in the graphene sheets can lead to the deep sub-wavelength confinement of terahertz wave and with Q-factor orders of magnitude higher than that of conventional 2DEG system at room temperature. Rooted in this understanding, the performance trade-off among signal attenuation, broadband operation, on-chip integrability can be avoided in future THz smart photonic network system by merging photonics and electronics. The unique properties presented can open up the exciting routes to compact solid state tunable THz detectors, filters, and wide band subwavelength imaging based on the graphene-FETs.
frequency applications. Recent progress on either back-gated or top-
gated graphene FETs integration with high-κ dielectric such as
$Al_2O_3$, has achieved mobility over 8000 cm$^2$/Vs at high charge
density and and 40000 cm$^2$/Vs at low charge density$^{35}$, making graphene
a potential candidate for THz nanoelectronics. In principle, the free
carrier density in graphene can be tuned by several orders of mag-
nitude ($10^{11} \sim 10^{14}$ cm$^{-2}$). Such unique property allows one to con-
trol strongly the plasma waves from far-infrared to terahertz
frequencies. However, there are still limited investigations on the
ac dynamics of Dirac fermions in FETs at THz frequency, and the
efficient excitation of plasma waves in graphene-FETs is imposed as a
key step towards future resonant detectors. Motivated by such aware-
lessness, in this work, we deal with the plasma wave excitation in the
channel-cavity of graphene-FETs. In the meantime, the screening
effects of metallic grating-gates/cooperative electric vibrators on the
plasma wave are explored for opto-electronic interconnect. The
strong change of optical transmission with wide voltage-tunability is
observed at the resonant frequency of plasma waves. These results
allow one to explore electro-optic properties of plasma waves based
on the configuration of graphene FETs, and can be used to build both
the ultra-fast THz modulators and the tunable detectors.

Results and discussions

The plasma wave and its quality factor $Q$ in FET-based THz-
detectors is commonly limited by the scattering of impurities and
phonons during the propagation of plasma waves. When the reso-
nant conditions is satisfied, the plasma waves excited by the incident
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Here, we employ the grating-gate to facilitate the excitation of
plasma waves and Fermi level modulation, and thus the grating-gate
serves both as the polarizer and electrode, as shown in Fig. 1(c),
where all the graphene sheets are connected to the same voltage
sources. Although various prototypes of graphene plasmonic
devices has been proposed at mid-infrared frequency, the Dirac
plasma waves in FETs and the screening effect of the metallic gate
in relative to the background absorption (see Materials and Methods)
or the frequency selectivity for tunable resonant detection. In addition,
the inverse of $\tau$ determines the linewidth of plasma wave reso-
nance, and the propagation distance of plasma waves is evaluated by
$\sim s\tau$ ($s$ denotes the plasma wave velocity). Therefore, samples with
higher momentum relaxation time $\tau$ are desirable for THz detection
or modulation. Even though the carrier mobility of graphene film
reported in the literature exhibits extreme variability from
$\sim 3000$ cm$^2$/Vs to 20000 cm$^2$/Vs under different growing conditions,
recent studies demonstrate that the intrinsic mobility can exceed
100000 cm$^2$/Vs in both single and bilayer graphene systems after
eliminating the scattering in the substrate, as shown in Table I. For
a moderate room-temperature mobility of 10000 cm$^2$/Vs at Fermi
energy $E_F \sim 0.4$ eV, the momentum relaxation time $\tau$ of the Dirac
fermions is 0.4 ps larger than that of III–V semiconductor, such as
Ga$N^{34,35}$. In the non-ballistic regime (e. g. longer channel length), the
decay of plasma waves along the propagation direction is exponential,
with $1/e$ characteristic length $l_{ch} \sim 2\,\mu m$ (4 $\mu m$ at $E_F = 0.1$ eV). In
the graphene FETs for terahertz detection, the channel of 2DEG
serves as a cavity, the standing plasma wave oscillation can be estab-
lished when the half-wavelength of plasma waves is commensurate
with the length of channel$^{25,29}$. Therefore, the resonant detection
with frequency tunability and selectivity can be easily realized if
the channel length $L$ is much less than the characteristic length.
In III–V semiconductors such as GaAs, InGaAs, such resonant condi-
tion requires the gate length shrinking down to 100 nm, in order
to reach plasma resonance over 1 THz (see Table II). However,
one of the major bottlenecks limits the room-temperature operation
of THz detection is the resonant broadening caused by the scattering
between gated and ungated plasma waves due to the long access
region in the architecture of FET$^{17,24}$. During the every reflection at
the boundary of channel cavity, the amplitude of plasma wave dete-
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dicted by the theory. Therefore, the graphene-based plasma-wave
FETs will potentially eliminate these deficiencies due to both the
highly tunable electron density (higher plasma velocity) and high
mobility.

Excitation of plasma waves and electrostatic screening effect in
FETs. Here, we employ the grating-gate to facilitate the excitation of
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Table I | Experimental mobility (cm$^2$/Vs) of monolayer, bilayer and multilayer graphene on different substrates

|            | SiO$_2$       | BN            | SiC           |
|------------|---------------|---------------|---------------|
| Monolayer  | 9 000–30 000$^{10}$ | 55 000–125 000$^{11}$ | 18 100$^{12}$ |
| Bilayer    | 3 000–12 000  | 40 000        | 6 000–10 000$^{14}$ |
| Multilayer | $\sim 10 000^{16}$ | 1 000–3 000$^{18}$ |               |

Table II | Quality factors of various III–V FETs (experimental) and the proposed one in this work

| Materials          | Room temperature mobility (cm$^2$/Vs) | Cyclotron mass (m$o$) | Quality Factor (Q) | Gate Length ($\mu$m) |
|--------------------|--------------------------------------|-----------------------|--------------------|----------------------|
| Monolayer Graphene | 10 000                               | 0.069                 | $-15.5 (6.39$ THz$)$ | 2.4                  |
| Bilayer Graphene   | 10 000                               | 0.104                 | $-29 (11.89$ THz$)$ | 2.4                  |
| (AB stacking)      | 10 000                               | 0.037                 | $-7.5 (6.85$ THz$)$ | 1.15                 |
| $\text{AlGaN/AlN}^{5}$ | $\sim 1200$                          | 0.059                 | $-20 (9.84$ THz$)$ | 0.05                 |
| $\text{InGaAs/InAlAs}$ | $\sim 7000$                          | 0.042$^{16}$          | $-2.5 (2.5$ THz$)$ | 0.15                 |
| $\text{AlGaN/AlAs}$ | 7480                                 | 0.063                 | $-5.5 (2.5$ THz$)$ | 0.16                 |
is commensurate with gate length \( (L) \). On the other hand, the wavelength of plasma waves can occupy the entire period \( (A) \) of the grating if \( f \sim 1 \). Due to the screening of the metallic grating-gates, the effective permittivity \( \varepsilon^* \) is determined by the thickness \( d \) of dielectric layer separating the graphene from electrodes and the period \( A \) or the plasma wavelength (see Material and Methods). Thus, the propagation of plasma waves in the gated and ungated channels follows different dispersion relationship\(^{36}\).

We tune the Fermi level from Dirac point electrically. Fig. 2(a) shows the plasma wave-induced THz optical absorption in graphene-FETs when the Fermi energy is 0.39 eV above the CNP (charge neutral point). There are rich veins of sharp resonances with frequency ranging from 2.5 THz to 30 THz are induced in the near-field zone of the electrodes (see Figs. 2(e) and (f)). It is shown that the quality factor \( (Q) \) of \( \sim 15 \) can be order of magnitudes larger than that of previous GaAs or GaN heterojunction FETs\(^{37}\) with the same dimensions (see Table II), and the absorption strength approaches to the maximum available value \( \sim 40\% \) (see Material and Methods), which is remarkable since the active device is only one-single layer. It is worth noting that period \( A \) of the present device is about two times and order of magnitude longer than that of AlGa\(n\)/Ga\(n\) and InAl\(A\)/InGa\(As\), therefore the quality factor presented here is a conservative estimation. Moreover, the resonances up to seventh order can be discernable from Fig. 2(a), which can be engineered to facilitate wider tunable THz detection or modulation beyond other available ones. Such results benefit from the potential highly tunable electron density from \( 10^{11} \) to \( 10^{14} \) \( \text{cm}^{-2} \) at CNP up to \( 10^{14} \) \( \text{cm}^{-2} \) or above and higher carrier’s mobility.

However, due to the relativistic electron transport properties caused by the linear dispersion, the plasma waves in graphene-FETs exhibit properties different from those in conventional 2DEG system with parabolic dispersions. Fig. 2(b) displays the scaling of graphene plasma waves under different gate voltages or Fermi levels. Unlike the conventional 2DEG, the plasma wave in graphene-FETs can not be simply described by employing the parallel plate capacitor model. The quantum capacitance effects in the graphene-channel are notable even with 50 nm thick dielectric layer due to its low density of states near Dirac point. Such effects cannot be neglected at higher order plasmon resonance (seen dashed line in Fig. 2(b)), and thus may play an important role in the near infrared or visible light region. The sub-linear frequency dependences of these resonances on Fermi energy and gate voltages are in consistent with theoretical predictions and experimental observations recently\(^{39}\). In parallel-plate capacitor model\(^{36,38}\), the frequency of plasma waves is approximately proportional to \( V_g^{-1/4} \) (\( V_g \) is the gate voltage) in theory, which is in contrast to the \( V_g^{-1/2} \) relation in 2DEG with parabolic dispersion\(^{31}\). However, in actual graphene device, the deviation from \( V_g^{-1/4} \) relation may take place if the quantum capacitance dominates over geometrical capacitance or the device has long ungated part of channel weakening the cavity confinement of plasma waves. Such phenomenon is slightly exhibited in Fig. 2b, where the voltage-induced frequency-shift of higher plasma waves (dashed line) departures from those at different Fermi levels (open symbols).

To understand better the intrinsic physical mechanism, Figs. 2(e) and (f) display the induced field distributions of resonances \( a \) and \( b \) along the channel of graphene-FETs. Due to the capacitive coupling between grating-gate and graphene, the intensity of optical-field is strengthened by more than 200 times. These figures also indicate that resonances \( a \) and \( b \) in the channel have two and four antinodes of field amplitude under the metal gate. The results also indicate that

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Figure 1 | Illustration of plasma waves in graphene FETs for terahertz detection and modulation. (a) The formation of plasmonic cavity with electric vibrator at top contact monitoring the conductivity of graphene channel, the bottom gate is used to tune the Fermi level, and the cascade cooperative plasma oscillation is formed, leading to the rectify and detection of THz radiation (see Supplementary Information). (b) The conical band structure and the optical process are shown. The plasmon enabled intraband electron transition is dominant due to the Pauli blocking and low density of states at Dirac point. (c) Left column: the proposed MGL-FETs with the stacked graphene sheets being connected to different or same voltage sources if needed, the grating contacts at the top side act both as electrodes and couplers. Right column: with an applied bias, the shift of Hartree band and the Fermi level accommodate the carriers’ distributions.
resonance B is the higher order mode of resonance A ($f_B: f_A \approx 2:1$). In addition, the half-wavelength of plasma wave is approximately in commensurate with the length of gate finger, in consistent with the above discussions. For plasma waves in the pristine graphene, the propagation constant, length and field-localization depend strongly on the dielectric environment ($\varepsilon$)(seeing Materials and Methods), the value of which can be tuned efficiently with the implementation of electrostatic-gating. Also, the tunability of dielectric environment can be explored to realize highly tunable THz waveguide. The resonance $C$ of Fig. 2(a) occurring at higher frequency is actually due to the ungated plasma wave with the similar in-plane dipole distribution along the channel. Fig. 2(c) displays the color plot of the resonant spectra with the change of Fermi energy or gate voltage. We find that higher order modes are growing up alternatively at higher Fermi energy or gate voltage. The results indicate the potential of graphene-FETs for wide-band THz applications. For more clarity, the transformations of resonances A, B and C are shown in Fig. 2(d), and non-monotonous dependence of resonant strength on the Fermi energy or gate voltage is observed. Interestingly, we find that both fundamental plasma mode A and C experiencing the process of resonant enhancement and damping near the critical Fermi energy $E_F \sim 0.4$ eV, and higher order mode B is growing up continuously. The behavior has not yet been observed in conventional 2DEG system, which may be concealed by the lower mobility and finite tunable range of electron density. In graphene, the plasma wave resonance is mainly determined by three phenomenological parameters (radiative loss, electron relaxation loss and nonradiative loss), among which the radiative loss can exceed the electron relaxation if the samples have higher mobility and higher Fermi energy (seeing Materials and Methods). Following such a way, the higher order plasma waves would be growing up alternatively as depicted in Fig. 2d.

**Plasma wave resonances in MGL-FETs and tunable dispersions.** Based upon the above results, it is known that the tunability of double-layer graphene FETs can be limited by the screening of carriers in the top-graphene channel and is poorer than that of the single-layer ones. The behavior can be understood intuitively after taking into account the fact that the top and bottom graphene layers share the same amount of carriers $Q_0$ as the electrodes. The frequency of the combined resonance in double-layer devices is obviously lower than that in single-layer ones with the same electron number $Q_0$ (seeing also the following discussions). In order to eliminate these drawbacks, we proceed to exploit the modification of plasma wave resonance in MGL-FETs with dielectric barrier-layers separating different graphene sheets as shown in Fig. 1(c), and the dielectric layer thickness is sufficient large that only the Coulomb interactions between those graphene layers are presented (seeing Supplementary Informations).

Fig. 3 illustrates the scaling behavior of plasma wave resonances in monolayer and strong coupling double-layer system. Unlike other results on graphene-dielectric grating system from where the
frequency of plasma wave resonance depends on the period $A$ only, the frequency of plasma waves propagating in graphene-FETs is inversely proportional to the gate length $\sim 1/L$, which may originate from the screening caused by the electrodes (see Materials and Methods). In strong coupling multi-layer graphene system (Fig. 3(e)), the screening between graphene-layer cannot be neglected and the “virtual gate” effect should be taken into account$^{39}$. In such cases, the graphene layer not only supports the plasma waves but also behaves like another electrode to tune the frequency. Therefore, the resonance frequency of plasma waves in the strong coupling limit should be modified as $\omega_p \propto (\sum_i n_i^* d_i)^{1/2}/L$, where $i$ is the layer index, $d_i$ is the separation between graphene layers, and $n_i$ is sheet charge density in the $i$th graphene layer. The results indicate that tunability of detector or modulator can be improved in separately electrical-controlled layers. The scaling scheme of frequency dispersion in the multilayer-FETs (five graphene sheets in Fig. 3(f)) is in good agreement with the assumption. Rewriting the law as, $\omega_p = CE_F^{1/2}$, one can see that multilayer graphene has larger coefficient $C$ than monolayer graphene, leading to the better electrical tunability. Meanwhile, the non-monotonic change of plasma wave resonance can also be resolved, and the intensity of the fundamental mode $A$ is starting to decline around Fermi energy $E_F \sim 0.45$ eV. As discussed above, it is expected that the intensity of higher order mode can be strengthened alternatively. Compared with the similar structure using the single graphene-layer, the fundamental mode of multilayer graphene can be tuned from 10 THz to 19 THz when the Fermi level increases from 0.15 eV to 0.59 eV, but the monolayer graphene can just be tuned only from 4 THz to 8 THz.

Furthermore, the above mentioned screening behavior can be clearly discernable in double-layer graphene device (Figs. 3(b) and (c)) when the separation $d$ between them is smaller than 60 nm. On the contrary, when the thickness $d$ exceeds 60 nm, the modified formula deviates obviously from the obtained results and the tunability of plasma wave is deteriorated arising from the poor coupling between these two graphene sheets. Furthermore, in Fig. 3(d), we can indeed see that the formation of “virtual gate” causes strong screening of electric-field spreading from the two channels in the device with 40 nm dielectric layer. The screening leads to the out of phase dipole oscillation of plasma waves between the two channels. However, the effect can be neglected in Fig. 3(e) with dielectric layer thicker than 100 nm, and obviously, the device behaves like that with only single-layer. Meanwhile, with only 60 nm thickness separation, the coupling strength between graphene sheets is decreased by more than four times. The results also demonstrate the strong field confinement of graphene plasma waves in deep-subwavelength regime. Other interesting findings in Fig. 3(e) is that the propagation of plasma

Figure 3 | Illustration of the scaling of plasma wave resonance and screening effect in MGL-FETs (Fig. 1(c) under different controllable parameters. (a) The frequency dependence of plasma waves in strong coupling double-layer device (Fig. 1(c)) with interlayer spacing $d \sim 50$ nm is proportional to the inverse of gate length $L$, the solid and open symbols are the first two resonances at $E_F \sim 0.21$ eV and $E_F \sim 0.29$ eV, respectively. (b) The screening (virtual-gate effect) between two graphene sheets affect obviously the dispersion of plasma wave resonance in the strong coupling limit ($d < 60$ nm), where the virtual gate effect dominates (Fig. 3(d)), and the tunability degrades to the monolayer plasma wave resonance if the interlayer spacing exceeds 60 nm, in the meantime, a sharp contrast in near-field strength is seen between Figs. 3(d) and (e). Also, the good agreement between “virtual gate” model and obtained data in Fig. 2(b) corroborates again the dominated role of screening (Fig. 3(c)). By increasing the number of graphene sheets, the plasma wave resonance can be tuned in wider frequency band (f). (g) is the schematic of the multi-waveguide-like FETs as proposed for nano-photonics making use of the strong screening effect and confinement of plasma wave in graphene. (i) Indicating the good agreement between effective medium model (seeing Materials and Methods) (open symbols) and obtained results (solid symbols). We find the sensitive tunable resonance and propagation constant or absorption in deep subwavelength regime from 0 nm to 200 nm (i.e., $\lambda/2d \sim 10^3$) (h), enabling the flexible design of monolithic THz photonic network system.
waves in lower channel is very similar to the ones in pristine graphene waveguide (seeing the following sections).

Furthermore, the multiple-waveguide-like FET structure with monolayer graphene serves as a transmission medium can be formed (Fig. 3(g)). The resonant frequencies in such configuration exhibit blue shift when the thickness $d_{\text{ox}}$ of the insulating layer increases, as shown in Figs. 3(h) and (i), due to the fact that the effective permittivity (seeing Materials and Methods) is in strongly correlation with the screening of electrodes. It is also clear that the resonant peaks scale vary rapidly with the changing of $d_{\text{ox}}$ in submicrometer range ($0 \sim 200 \text{ nm}$) and can be well fitted by the effective medium model (Fig. 3(i)). Except for the shift of the resonances, the intensities also depend strongly on the thickness of the insulator from $0 \text{ nm}, 200 \text{ nm}$. It is indicated that the propagation length $L_{\text{p}}\sim (2\pi h_{\text{e}}/e^2\omega)^{-1/2}$ of plasma wave can be optimized in deep subwavelength regime according to different purposes as expected. The result also inspires us to develop compact terahertz waveguide (seeing Supplementary Information) in more controllable ways and facile monolithic integration with existing solid-state terahertz sources, such as quantum cascade lasers, backward diodes etc.

Fig. 4 presents the oscillations of plasma waves in monolayer and multi-layer graphene devices in the absence of metallic screening. The side contacts of devices serve both as electrodes/electric-vibrators for photon detection or slot-line for THz plasma waveguide (Fig. 1(a)). In monolayer device, three kinds of guide mode resonances can be excited independently with similar modal characteristics as the results reported above (Figs. 4(d)–(f)). We find that in the device with only single graphene sheet, two modes originate from the hybridization of edge-graphene-plasma waves (EGP)\(^{41}\). Due to the splitting, one of two modes with the field distribution being localized at the edge is similar to the even-parity edge mode (Fig. 4(d)) in freestanding graphene nanoribbon, and another is similar to the guided edge mode with odd parity (Fig. 4(e)). In addition to EGP, the so-called waveguide-graphene-plasma waves (WGP) with electric polarization extending over the entire ribbon width can also be excited (Fig. 4(f)). In similar to the aforementioned plasma waves, such WGP mode is activated when the half-wavelength is commensurate with the separating between side contacts. It should be noted that the near-field strength of WGP mode is an order of magnitude stronger than other two edge modes. The results indicate the potential of the graphene device for deep-subwavelength imaging. The hybridization of plasma waves has originally been investigated on GaN and AlGaAs/GaAs double quantum wells\(^{42,43}\). Here only OP (optical plasma) plasma waves can be observed in double-layer graphene FETs due to the small net dipole of AP (acoustic plasma) mode. The reduced symmetry between upper and lower graphene channel is reflected in the combination of different plasma waves in the two channels (Figs. 4(g)–(i)), which can be inferred from the dielectric structure above and below the individual graphene sheet. In these figures, more node-number of plasma waves can be seen in the lower channel. It is indicated that there is larger effective dielectric polarization suppressing plasma wave oscillation of the FETs, in consistent with the above results. In addition, the multi-resonance can be developed by increasing the number of graphene layers or introducing the nonsymmetric structures into the graphene plane. For example, we find the splitting of plasma resonance in the device

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**Figure 4** | The hybridization modes in monolayer and multi-layer graphene FETs, as shown in Fig. 1(a), (a)–(c) the spectral characteristics of plasma waves in monolayer (a), double-layer (b) and four-layer devices (c), in which the Fermi level can be tuned separately. We find the enhancement and splitting due to the interaction between Edge and Waveguide plasma waves. (d)–(f) displays elementary plasma waves in monolayer graphene-FETs, (d) and (e) illustrate the Edge-graphene-plasma waves (EGP), and (f) illustrates Waveguide-graphene-plasma waves (WGP). (g)–(i) demonstrate the interaction between WGP modes with different node numbers along the two channels of double-layer FETs. The oscillating charges are all extracted and shown along the channels.
with four layers and resonance up to 7th order occurs in single-layer ones (Figs. 4(a)–(c)), and activation of AP mode when the channel length between upper and lower channel is different. All these results illustrate potentially wide tunable THz/far-infrared detection of graphene, meanwhile, the plasma wave will cause the modulation and control the polarization of incident waves (see Supplementary Information), and thus enabling the realization of monolithic THz spectrometer.

Conclusions
In summary, we have introduced novel graphene-based FETs with the plasma waves acting as a new quasi-particle to transfer THz signal. Owing to its intrinsic high transport velocity and mechanical flexibility, the plasma wave devices yield very promising properties, including high sensitivity and wide-band tunability throughout the entire THz domain. The multiple guide-wave resonances in the graphene plane create deep sub-wavelength confinement of plasma wave and lead to Q-factor an order of magnitude higher than that of conventional 2DEG system at room temperature. Such unique properties enable the potentially application of graphene-based properties to THz electronic devices.

The surface resonant layer model. Such model\textsuperscript{44} treats the whole structure as a single plane with an analytic form of surface admittance $Y_{\text{d}}(\omega) = \sigma_{\text{d}}/\omega$ and $\sigma_{\text{d}}$ is the total self-consistent electric field can be resonantly enhanced by the plasma wave. At the plasma wave resonance, the Fourier amplitude of self-consistent field is $|E_{\text{ext}}|/Q|\omega|^{1/2}$. Therefore, the maximum available absorption is 50% of incident radiation. In the regime of off-resonance, only the Drude absorption can be introduced, and leads to the broadband THz detection.

Methods
The dispersion of 2D plasma waves in FETs. In the long wavelength limit, the Bohr radius of Dirac fermions is far less than the periodic perturbation of charge density of conventional 2DEG system at room temperature. Such unique properties enable the potentially application of graphene-based properties to THz electronic devices.

The hydrodynamic nonlinearity. The hydrodynamic nonlinearity of 2D electron fluid originates from its intrinsic correlation between electron velocity and density.

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Author contributions
L.W. performed major part of numerical experiments and written the paper. A.Y. performed simulation study of Fig. 3 and tunable graphene waveguide, filters in the Supplementary Information. Y.Z. and J.Y.D. performed numerical analysis of electrostatic effect. W.L. and X.S.C. developed the optical models of graphene plasma waves. All authors discussed the simulation results.

Additional information
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