The gate-controllable complex conductivity of graphene offers unprecedented opportunities for reconfigurable plasmonics at terahertz and mid-infrared frequencies. However, the requirement of a gating electrode close to graphene and the single ‘control knob’ that this approach offers limits the practical implementation and performance of these devices. Here we report on graphene stacks composed of two or more graphene monolayers separated by electrically thin dielectrics and present a simple and rigorous theoretical framework for their characterization. In a first implementation, two graphene layers gate each other, thereby behaving as a controllable single equivalent layer but without any additional gating structure. Second, we show that adding an additional gate allows independent control of the complex conductivity of each layer within the stack and provides enhanced control on the stack equivalent complex conductivity. These results are very promising for the development of THz and mid-infrared plasmonic devices with enhanced performance and reconfiguration capabilities.
The strong graphene–light interaction has led to the rapid development of graphene plasmonics1,2, which benefit from the unique electrical properties of graphene in the terahertz (THz) and mid-infrared frequency bands3. The characterization of single-layer graphene structures has already been done for microwaves4–7, THz7–9 and optics3,10, and some promising applications such as modulators11–16, plasmonic waveguides17,18 and Faraday rotators19 have been developed. However, the simple implementation and performance of these devices might be hindered by the presence of a gating electrode located close to graphene and the relatively weak control that this approach offers over the conductivity of graphene11,20. These limitations can be overcome by using graphene stacks, structures composed of two or more isolated graphene layers separated by electrically thin dielectrics, which lead to increased conductivity and may provide novel reconfiguration strategies.

Optical plasmons and quantum transport in such structures have already been studied theoretically21–23, whereas some experimental studies have focused on the Anderson localization of Dirac electrons in one of the graphene layers at DC due to the screening effect24–26. Furthermore, the Coulomb drag of massless fermions has been experimentally measured27, while both intra- and interlayer phenomena in structures surrounded by various dielectrics and their influence in the supported in-phase and out-of-phase plasmons have also been considered28,29. Potential applications of graphene stacks include modulators12, enhanced metasurfaces30, antennas31, or plasmonic parallel-plate waveguides18,32, among many others. Experimentally, graphene stacks have recently been applied to the development of vertical field effect transistors (FET) transistors33,34. In addition, the response of unbiased graphene stacks and devices at infrared frequencies has also been investigated20.

In this context, our work here demonstrates the concept of reconfigurable graphene stacks for THz plasmonics and presents a simple and rigorous theoretical framework for their characterization. Although the graphene monolayers within the stack are not close enough to couple through quantum effects26,34, their extremely small separation in terms of wavelength allows the stack to behave as a single equivalent layer of increased conductivity. The enhanced tunable capabilities of the proposed structure are experimentally demonstrated in different scenarios, including the mutual gating between the graphene layers and the independent control of each sheet through two different biasing gates. The measurement of the total stack conductivity \( \sigma_S \) for various combinations of gate voltages permits not only the extraction of the different parameters that define each of the layers but also the determination of the effective gate capacitance of the surrounding dielectrics. The proposed formulation also allows the design of structures with the desired tunable conductivity behaviour. Our results show that reconfigurable graphene stacks boost the available range of complex conductivity values provided by single-layer structures, thus facilitating the easy implementation of THz and mid-infrared plasmonic devices with enhanced reconfiguration capabilities.

**Results**

**Operation principle of reconfigurable graphene stacks.** The structure under analysis is shown in Fig. 1, where incident and transmitted beams required for THz time-domain measurements have been artistically rendered. The sample consists of two chemically vapour deposited (CVD) graphene monolayers separated by an electrically thin (\( d \approx 80 \text{ nm} \)) polymethylmethacrylate (PMMA) layer. Metal contacts, added using optical lithography followed by the evaporation of 50 nm of gold, have been included for biasing purposes. The sample is measured in the 0.5–2.5 THz frequency range using time-domain spectroscopy. The complex conductivity of the graphene stack is then retrieved using a dedicated formulation35,36. Details regarding the fabrication, measurement and stack conductivity extraction process are provided in Methods. As the dielectric separation layer between the graphene layers is extremely thin in terms of wavelengths20 (\( d/\lambda_0 \ll 10^{-3} \)), an incoming electromagnetic wave observes a stack conductivity \( \sigma_S \)

\[
\sigma_S = \sigma_{\text{top}} + \sigma_{\text{bot}},
\]

where \( \sigma_{\text{top}} \) and \( \sigma_{\text{bot}} \) are the complex conductivity of the top and bottom graphene layers, respectively. Figure 1c plots the frequency-dependent real and imaginary parts of the extracted conductivity \( \sigma_S \) for several DC biasing voltages applied between the graphene layers. In the low THz band, the real component of the sample conductivity does not vary with frequency, whereas the magnitude of the imaginary part, which facilitates the
Figure 2 shows the measured reconfiguration capabilities of the fabricated graphene stack at $f = 1.5$ THz in different scenarios. In the first case, depicted in Fig. 2a, a gate voltage $V_{DC}$ is applied between the two graphene layers. The results clearly confirm the tunability of $\sigma_s$ and the ability of the stack to self-bias. The extracted chemical potentials corresponding to each graphene sheet, computed using the procedure detailed in Methods combined with the measured stack conductivity and further validated by Raman scattering measurements, are depicted versus the applied gate voltage in Fig. 3. Both graphene layers are $p$-doped and they present slightly different Fermi levels. This difference can be due to the defects induced in the graphene layers during growth or transfer and to the influence of the surrounding dielectrics. In addition to the different morphology of the surrounding dielectrics, contamination during processing and molecules absorbed from ambient air play a crucial role. Applying a positive bias between the graphene sheets injects electrons/holes into the top/bottom layers, as illustrated in Supplementary Fig. 1, which in turn increases/decreases their chemical potential (or vice versa in the case of a negative applied bias). Furthermore, the extracted conductivities and chemical potentials exhibit a hysteresis behaviour, which arises due to the charges and impurities trapped in the surrounding dielectrics, as occurs in graphene transistors.

Another interesting possibility for controlling the stack conductivity and boost its tuning range consists of applying voltages $V_1$ and $V_2$ to the bottom and top graphene layers, as illustrated in Fig. 2b. For the sake of simplicity, we have implemented this biasing scheme by including an additional polysilicon gate below the lower graphene layer. Alternatively, this configuration might be implemented by stacking a higher number of graphene layers in the same structure. Finally, Fig. 2c presents a simple biasing procedure able to control the conductivity of each layer independently. Specifically, applying a fixed voltage $V_2-V_1$ between the graphene sheets fixes the chemical potential of the top layer, whereas the carrier density on the bottom layer is tuned by modifying the voltage $V_1$, as will be theoretically demonstrated below. Note that a voltage $V_1 = 0$ V does not exactly simplify this experiment to the one of Fig. 2a, due to the weak electrostatic fields that may arise between the bottom graphene sheet and the polysilicon layers in practice (see Methods). The examples illustrated in Fig. 2 demonstrate the large potential of graphene stacks for THz plasmonics, as it is possible to control the behaviour of the different layers within a unique stack to achieve the complex conductivity required for a desired application.

Figure 2 | Reconfiguration capabilities of the fabricated graphene stack. (a) Measured conductivity plotted versus a voltage $V_{DC}$ applied between the two graphene sheets. Simulated results are included for comparison purposes. (b) Measured conductivity plotted versus the voltage $V_2$ applied to the top graphene sheet for different values of the bottom gate voltage $V_1$. (c) Measured conductivity plotted versus the voltage $V_2-V_1$ applied between the graphene layers for different values of the bottom gate voltage $V_1$. The different insets illustrate the sample cross-section and its connection to the voltage sources. For the sake of clarity, the hysteresis behaviour of the stack conductivity has been removed in cases b and c. The operation frequency is set to $f = 1.5$ THz.

Static and dynamic characteristics. The graphene stack is theoretically analysed in two different but interdependent steps. First, the carrier density on each graphene layer is determined as a function of the applied gate voltages using an electrostatic approach. Second, this information is employed to compute the frequency-dependent conductivity $\sigma_s$ of the stack. In a general case of two graphene sheets biased by different voltages $V_{DC}$ and $V_s$ (see inset of Fig. 2b and Supplementary Fig. 1), these carrier densities can be approximated as

$$q n_{top}^s = q n_{top}^b - C_{ox}^{top} (V_2 - V_1), \tag{2}$$

$$q n_{bot}^s = q n_{bot}^b + C_{ox}^{top} (V_2 - V_1) - C_{ox}^{bot} V_1, \tag{3}$$

where $-q$ is the electron charge, $n_{top}^s$ is the total carrier density in the $p$ graphene layer (with $p = \{\text{bottom,top}\}$), $n_{bot}^s$ corresponds to the pre-doping of the $p$ sheet and $C_{ox}$ is the capacitance of the $p$ dielectric layer. Once the carrier densities are known, the Fermi level of each graphene layer and the conductivity $\sigma_s$, which determines the electromagnetic behaviour of the whole stack, can be easily computed (see Methods for details). Moreover, equations (2) and (3) further confirm that it is possible to
control the conductivity of each graphene layer independently. Specifically, the carrier density on both layers similarly depends on the difference between the applied voltages ($V_2$–$V_1$), while the bottom layer additionally depends on the voltage $V_1$. Consequently, modifying the voltage $V_1$ while keeping constant the difference $V_2$–$V_1$ allows the independent control of each layer’s conductivity.

This simple framework allows a rigorous extraction of the characteristics of the stack from the measured data, including the relaxation time ($\tau_0$) and the Fermi level ($\mu_c$) of the graphene layers and the capacitance ($C_{\text{ox}}$) of the surrounding dielectrics. This procedure, detailed in Methods, relies on applying different sets of gate voltages to the sample to measure various stack conditions, which in turns allows independent extraction of all of the aforementioned parameters. A system of nonlinear coupled equations is then imposed, relating the measured data to the theoretical characteristics of the stack. In the particular case of the sample shown in Fig. 2a, the solution of the system of equations yields $\tau_{\text{top}} = 0.033$ ps, $\tau_{\text{bot}} = 0.03$ ps, $\mu_{\text{top}} = -0.4$ eV and $\mu_{\text{bot}} = -3.355$ eV, whereas the gate capacitance of the PMMA separation layer is $C_{\text{top}} = 3.2 \times 10^{-4}$ F m$^{-2}$. These values are in good agreement with the measured characteristics of a single-layer graphene transferred onto a similar dielectric ($\tau = 0.029$ ps and $\mu = -0.425$ eV, as shown in the Supplementary Figs 2–4) and with the gate capacitance obtained using the approximate parallel-plate formula $C_{\text{ox}} = \frac{\epsilon_0 \epsilon_r}{d} \approx 3.315 \times 10^{-4}$ F m$^{-2}$. The simulated results, plotted in Fig. 2a and Fig. 3 together with measured data, confirm the accuracy of both the extraction procedure and the proposed model to characterize reconfigurable graphene stacks. The measured hysteresis behaviour of the sample conductivity, which is mainly related to the charges trapped in the dielectrics surrounding the graphene layers,$^{45}$ is not considered in the model. In addition, the extracted values permit estimating a modulation speed of 6.2 kHz for the stack (see Supplementary Note 1), similar to the one found in single-layer graphene structures$^{12,46}$.

This framework can be further employed to forecast the reconfiguration capabilities of a wide variety of graphene stacks, allowing the design of structures with desired plasmonic properties and tunable behaviour. Figure 4 illustrates at $f = 1.5$ THz the real and imaginary conductivity components of a stack composed

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**Figure 3 | Extracting the chemical potentials of the two layers composing the graphene stack.** Results are computed versus the applied gate voltage $V_{\text{DC}}$ (see inset of Fig. 2a), as detailed in Methods. Additional results obtained by measuring the dopants of the top layer using a Raman scattering technique$^{38}$ (at $V_{\text{DC}} = 0$ V) and by the proposed theory are included for comparison purposes.

**Figure 4 | Theoretical reconfiguration capabilities of various graphene stacks.** Results are computed versus the type of doping of the stacks composing layers. A biasing voltage $V_{\text{DC}}$ is applied between the graphene sheets, as illustrated in the inset of Fig. 2a. The type of doping of the layers follows the nomenclature $TB$, where $T = (N, P)$ and $B = (N, P)$ are related to the top and bottom layers, respectively, and $(N, P)$ refers to n-doped or p-doped graphene. The upper row shows the real (a) and imaginary (b) conductivity components of a stack composed of layers with opposite Fermi level. (c,d) Similar results for the case of a stack composed of layers with equal Fermi level. Other parameters are $f = 1.5$ THz, $\tau_{\text{top}} = \tau_{\text{bot}} = 0.03$ ps and $T = 300$ K.
by two graphene sheets with various Fermi levels versus the gate voltage applied between the layers (see inset of Fig. 2a). Let us first consider, for simplicity, a stack where the graphene layers have a different type of doping, that is, one sheet is $p$-doped and the other is $n$-doped. In this particular case, illustrated in Fig. 4a,b, the carriers injected by the voltage source alter the carrier density on each layer in a similar way, that is, simultaneously increasing/decreasing their $|\mu_c|$, while keeping their opposite doping nature $\text{sign}(\mu_c^{\text{top}}) \neq \text{sign}(\mu_c^{\text{bot}})$. As a result, the stack conductivity is approximately twice the conductivity of an individual layer. The behaviour of the stack conductivity differs with respect to the previous case when the layers have the same type of doping, that is, if they are both $p$-doped or $n$-doped. In this case, shown in Fig. 4c,d, the carriers injected by the source modify the carrier density on each graphene sheet in an opposite direction, that is, increasing $|\mu_c|$ of one layer while reducing it on the other layer. Consequently, the stack conductivity presents a symmetrical behaviour for positive and negative gate voltages, exhibiting points of minimum conductivity in both cases. The results shown in Fig. 4 confirm that in graphene stacks, (i) the imaginary component of $\sigma_s$ can be double than the one of a single-layer structure, while avoiding the presence of metallic bias, and (ii) the tuning range is significantly boosted for similar applied voltages values.

In addition, the conductivity of graphene stacks can be controlled further by considering two different gate sources, as shown in the inset of Fig. 2b. Similar to the previous case, the tunable behaviour of the stack conductivity will strongly depend on the initial level and the type of doping of each graphene layer, leading to a wide variety of scenarios and reconfiguration possibilities (see Supplementary Figs 5–9).

**Surface plasmons supported by graphene stacks.** The measured characteristics of the fabricated stack allows to simulate the frequency-dependent properties of the surface plasmons supported by the device. Specifically, the structure supports two different modes$^{32,47}$ (see Methods): an even transverse magnetic (TM) and an odd quasi transverse electromagnetic (TEM). The former can easily be seen as a usual TM plasmon propagating along a single-layer graphene sheet, with a conductivity equal to the stack conductivity $\sigma_s$. Figure 5a illustrates the characteristics of this mode, which presents lower-field confinement and reduced tunability compared with plasmons in single-layer graphene. This behaviour arises due to the increased imaginary component of the stack conductivity, which in turn reduces the kinetic inductance associated to this mode. The later is a perturbation of the TEM mode found in standard parallel-plate waveguides with two perfect electric conductors. Figure 5b confirms that this mode presents remarkable characteristics in terms of field confinement and tunability, clearly outperforming single-layer graphene structures. Note that the high losses associated to CVD graphene$^{48}$, which prevent the propagation of the supported plasmons along many wavelengths, can be significantly mitigated by employing high-quality graphene in the stack$^{49}$. Supplementary Note 2 includes a comparison of the characteristics of plasmons supported by the stack and a single-layer graphene structure, and further discusses the influence of losses in both cases.

**Discussion**

This theoretical and experimental study of graphene stacks has demonstrated that the available range of complex conductivities in graphene stacks can be significantly boosted by two different approaches as follows: (i) mutually biasing the graphene sheets without requiring the presence of any metallic bias and (ii) including a third gate source to control the conductivity of each layer independently. The development of graphene stacks for THz plasmonic also faces some important challenges from the technological point of view, as it would be desirable to independently control the doping nature of each layer while decreasing the separation distance between the graphene sheets, to further enhance the reconfiguration possibilities of the stack. Furthermore, interlayer Coulomb effects$^{28,29}$ should be rigorously taken into account in stacks with very small (approximately nanometres) separation distances between their layers. In addition, it would be also interesting to extend the concept of reconfigurable stacks to an arbitrarily large number of layers. The exotic characteristics of graphene stacks paves the way towards the development of a low-dimensional plasmonic platform with enhanced performance and reconfiguration capabilities. For instance, graphene stacks are the building block of the recently proposed tunable bulk hyperbolic metamaterials$^{30}$, whereas it has also demonstrated that they are able to boost the spontaneous emission of emitters$^{51}$ much further than the usual monolayer graphene structures$^1$. In a different context, the large range of imaginary conductivity values provided by the stacks can easily be exploited in planar hyperlenses. Currently, graphene-based hyperlenses$^{52}$ are based on achieving large contrast of conductivities within the surface by using non-uniform metallic gates located very close to graphene. However, these gates are difficult to fabricate and impair the performance of the lenses. This device could easily be implemented by a patterned graphene stack, simultaneously solving the problems related to the limited
values of the imaginary conductivity and the presence of the non-uniform metallic gate. Finally, it is noteworthy that the aforementioned features of graphene stacks can also be applied to develop improved devices such as modulators, isolators, sensors or antennas in the THz and infrared frequency bands.

Methods

Fabrication of single-layer and stack graphene structures. The samples were fabricated using CVD graphene grown on Cu foil and transferred onto the substrates using the standard wet transfer method. An alternative transfer method shows the flow of the fabrication process for the double-layer graphene stack. We deposit 72 nm of Al₂O₃ by atomic layer deposition (ALD) on a p-type Si wafer. The ALD is performed at 200 °C using trimethylaluminum and distilled water as the reaction precursors. Before the dielectric deposition, the native oxide is removed from the Si wafer with a buffered oxide etch. The metal electrodes are patterned by optical lithography followed by a deposition of 5 nm of chromium, 50 nm of gold and a lift-off process. A graphene sheet is then transferred onto the top of one of the metal contacts. In the double-layer graphene stack, the PMMA layer used as a support polymer during the transfer process is kept on top of the graphene to act as a dielectric between the two graphene sheets. The second graphene monolayer is subsequently transferred onto the top of the other predefined metal contact, thus obtaining the final structure shown in Supplementary Fig. 10d.

The Raman spectra of the graphene employed in our devices is shown in Supplementary Fig. 11. The G and 2D band points are located at 1,589 and 2,682 cm⁻¹ with a full width at half maximum of 18 and 32 cm⁻¹, respectively. The intensity ratio of the 2D to the G band and of the D to the G band are 5.5 and 0.09, respectively. All of these numbers are typical hallmarks of monolayer graphene. The use of spin-coated PMMA as a separation layer between the graphene sheets allows the avoidance of problems associated with standard transfer methods. This approach is valid here, thanks to the extreme fineness of the PMMA layer (approximately nanometres) dielectrics but is completely negligible here.

THz time-domain measurements. The measurements at THz frequencies were performed using a commercial Time Domain Spectrometer (Menlo TERAMBI), which consists of a pulsed femtosecond laser at 780 nm with a pulse repetition rate of 100 MHz and a pulse width around 110 fs, offering with the current experimental setup a signal-to-noise ratio of 40 dB up to 2.5 THz. Two photoconductive antennas based on LT GaAs (Teravolt-1) are used to generate and detect the THz radiation. A set of lenses focuses the THz beam onto the sample under measurement. The total sample area illuminated by the beam is around 2 mm², thus averaging graphene’s features (see Supplementary Note 3). Supplementary Fig. 12 presents a schematic view of the experimental setup, with the disposition of the samples and voltage sources.

The gating was applied using a four-channel DC voltage source, Agilent N6700B. Only two channels were used for the measurements and each channel was connected to a different gold contact corresponding to a graphene layer, whereas they both shared a common ground gold contact. For safety reasons and to prevent damaging the graphene stack, the maximum voltage (taking into account both sources) was limited to 25 V. The sample was positioned on an X-Y stage perpendicular to the THz beam and everything was placed inside a sealed case purged with N₂ to keep a constant atmosphere during the duration of the measurements.

Stack conductivity extraction. The stack conductivity σₖ is extracted from the THz time-domain measurements, using standard thin-film characterization techniques. This approach is valid here, thanks to the extreme fineness of the stack in terms of wavelength (d/λ < 0.1%). An example of the different set of measured pulses employed for the extraction procedure is shown in Supplementary Fig. 13. To keep the higher possible signal-to-noise ratio, we have considered only the first transmitted pulse through the sample. Additional transmitted pulses that arise due to the internal reflections of the THz beam within the layers of the sample are clearly identified, thanks to their temporal delay, and subsequently removed.

The graphene stack is not free standing, but on top of a thick dielectric structure. Consequently, the influence of the dielectrics must be rigorously removed to extract the actual stack conductivity. This procedure has been performed as follows: (i) a pulse is transmitted without the presence of any sample to measure and store the response (including atmosphere and possible impurities) of the sealed cage. (ii) A pulse is transmitted through an area of the sample free of graphene, which remains bare. The combination of this measured pulse with the pulse obtained in the previous step allows the extraction of the stack conductivity, loss tangent and thickness of the dielectrics using standard techniques. (iii) A pulse is transmitted through the graphene stack sample. Combining this measured pulse with the previous information, it is indeed possible to extract the conductivity of the graphene stack rigorously removing the influence of the dielectrics and surrounding atmosphere.

Graphene stack theory. The frequency-dependent conductivity σ of a single graphene layer is modelled using the Kubo formalism as

\[ \sigma(\omega, \mu, \epsilon, \Gamma) = \frac{\hbar}{4\pi} \left[ \frac{1}{(\epsilon_{\omega} - 2\Gamma) + i\omega} \int_0^{\infty} \frac{d\epsilon}{\epsilon} \frac{\partial f(e)}{\partial \epsilon} \frac{\partial f(-e)}{\partial \epsilon} \right] \]

where \( \omega \) is the radian frequency, \( \epsilon \) is energy, \( \Gamma = 1/2\tau \) is a phenomenological electron scattering rate assumed independent of energy, \( \tau \) is the electron relaxation time, \( T \) is temperature, \( \mu \) is the charge of an electron, \( B \) is the reduced Planck’s constant and \( f_{\pm}(e) \) is the Fermi–Dirac distribution defined as

\[ f_{\pm}(e) = \left( e^{\pm (\epsilon - \mu)/kT} + 1 \right)^{-1} \]

\( \mu \) being the chemical potential and \( k_B \) the Boltzmann’s constant. This model results from the long wavelength limit of the bosonic momentum \( k = 0 \) and takes into account both intraband and interband contributions of the graphene conductivity, as well as a finite temperature.

In addition, the carrier density \( n \) and chemical potential of the graphene layer are related through

\[ n = n_e - n_h = \frac{2\pi}{\hbar^2} \int_0^{\infty} \frac{\epsilon f(\epsilon - \mu_e) - f(\epsilon + \mu_h)}{\epsilon} d\epsilon \]

where \( n_e \) and \( n_h \) are the electron and hole densities, respectively, \( \epsilon \) is the energy and \( \mu_e \) and \( \mu_h \) are the Fermi velocity (\( \sim 10^6 \text{cm s}^{-1} \)) in graphene.

Let us consider the case of two graphene layers closely located within a stack, as depicted in Supplementary Fig. 1. As previously stated, the structure is analysed by using an electrostatic approach, which determines the carrier density on the graphene layer, and then obtaining the electromagnetic behaviour of the stack at THz. Following the superposition principle (see Supplementary Fig. 1b), the carrier density on each layer is computed using equations (2) and (3). Note that this electrostatic approach approximates both graphene and polysilicon for infinite perfect conductors, to compute the carrier density on each layer. Consequently, it cannot predict the presence of weak electrostatic fields that may arise due to (i) the different DC conductivities that graphene and polysilicon present in practice and (ii) fringing effects at graphene borders. Combining these expressions with equation (6) permits the chemical potential on each graphene layer to be determined. Once these potentials are known, the frequency-dependent complex conductivity of the individual graphene sheets is retrieved using equation (4), thus allowing the total graphene stack conductivity to be computed using equation (1). Note that in this approach we have neglected (i) the different DC conductivities that graphene and polysilicon present in practice, (ii) the influence of the separation layer and (iii) the finite temperature. However, it does not hinder the performance of the stack, as (i) the device does not operate at DC but in the THz band; and (ii) the graphene field’s effect control is preserved, as the DC biasing voltage source is able to provide the required bias voltage, hence the required electrical field, even when leakage current occurs.

In addition, note that monolayer graphene devices have been annealed in a N₂ atmosphere at 200 °C during 4 h (ref. 56). The annealing aims removing possible graphene contamination by polymer residues and other impurities. However, this process has not been applied to the graphene stack samples, because it would prevent the PMMA layer that isolates the two graphene sheets.
depicted in Supplementary Fig. 1. The availability of the total stack conductivity $\sigma_s$ for various combinations of gate voltages not only permits the extraction of the different parameters, which define each of the layers, but also determines the effective gate capacitance of the surrounding dielectrics. Specifically, given a measured stack conductivity $\sigma_s$ obtained by applying a set of gate voltages ($V_1$, $V_2$), equation (1) holds. This equation relies on the top and bottom complex conductivities of the layers ($\sigma_{top}$, $\sigma_{bot}$), which are computed using the Kubo formula (equation (4)) and depend on their relaxation time ($\tau_{top}$, $\tau_{bot}$). Fermi levels ($\phi_{top}$, $\phi_{bot}$), gate capacitance of the surrounding media ($C_{top}$, $C_{bot}$) and the applied gate voltages. Considering a set of $N$ measured stack conductivity values, obtained by applying different gate voltages, permits the extraction of equation (1) into a set of nonlinear coupled equations. The numerical solution of this system of equations determines both the characteristics of each graphene layer within the stack and the stack capacitance of the surrounding media. The solution of these equations may differ slightly as a function of the measured conductivity data employed as an input. These small variations are related to diverse factors, including the hysteretic stack conductivity$^{43}$ or the possible change in the environmental conditions$^{44}$. To take them into account, the various parameters extracted from all possible combinations of gate voltages are finally averaged. Employing a curve fitting approach is not straightforward here, as this would involve fitting six independent variables, which could lead to non-physical parameter values and complicated post-processing steps.

Surface plasmons supported by a graphene stack. The dispersion relation of the plasmonic modes supported by a graphene stack can be computed as$^{47}$

$$\text{eq}_{\phi} = \text{eq}_{\phi} + i\text{eq}_{\phi} = 0$$

where

$$\text{eq}_{\phi} = \frac{\sigma_{top}}{\sigma_{top} + C_{top}} \cos(k_{z2}) 
\text{eq}_{\phi} = \frac{\sigma_{bot}}{\sigma_{bot} + C_{bot}} \sin(k_{z2})$$

and $k_{z2} = k_{z1} - k_{z2}$, $z$ is the direction normal to the structure and the subscript $i = 1, 2, 3$ refers to the top (air), inner (PMMA) and bottom, $(Al_{2}O_{3})$ dielectrics. In addition, $k_i$ denotes the wavenumber of the medium and $k_i = \beta - j\omega\varepsilon_i$ is the complex wavenumber of the propagating plasmon. Note that we impose $k_{z1}/k_{z2} < 0$, to fulfill Sommerfeld’s radiation condition and we assume that the stack width $W$ is much larger than the guided wavelength (that is, $W \gg k_{z2}$). The supported even-TM and odd-TE modeshapes can be accurately modelled using per-unit-length equivalent circuits$^{25,49}$ (see Supplementary Note 2).

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Author contributions
J.S.G. and J.P.C. conceived the idea of reconfigurable graphene stacks as well as their application in THz plasmonics. J.S.G. developed the theory and analysed the measured data. C.M. and A.I. fabricated the devices. L.S.B. and A.M. grew and transferred the graphene layers. S.C. and J.R. performed the THz measurements. J.S.G. wrote the manuscript (with comments from J.P.C and S.C.). J.P.C. led the project.

Additional information
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