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GRAPHENE PLASMONS

Telecom meets terahertz

Excitation and gate tuning of terahertz plasmons in dual-layer graphene integrated into on-chip telecom photonic waveguides using infrared lasers has now been demonstrated. This may open the door to atomically thick optoelectronic devices for security, tomography or data processing.

Alexey Y. Nikitin

erahertz (THz) radiation (with wavelengths ranging from 0.03 to 3 mm) is extremely attractive for many vital applications such as communications, security, molecular recognition and medical imaging, among others¹. However, compact technology for the generation and manipulation of THz radiation is still in its infancy. In particular, its use at the nanoscale (where the THz waves would need to be compressed to deeply subwavelength volumes — far below the classical diffraction limit), which is desirable, for example, for high-resolution THz imaging or sensing of small amounts of matter, has been elusive so far and, until now, has been seen only as a future perspective. For these reasons, the pursuit of novel materials able to produce and guide THz waves is appealing.

Recently, graphene — a single layer of carbon atoms — has emerged as a versatile playground for many different photonic and electronic technologies², surpassing other materials in terms of its atomic thickness, flexibility, high carrier mobility and tunability. In infrared and, most importantly, in THz frequency ranges, doped graphene shows metallic behaviour due to the presence of a large amount of free charge carriers, with their concentration reaching 10^{11} – 10^{12} cm⁻². As a result, graphene can trap light in the form of plasmon polaritons - collective oscillations of charge carriers coupled to the electromagnetic field. A strong scientific and technological interest in graphene plasmon polaritons (GPPs) has recently arisen due to their ultrashort wavelength compared with that of freespace photons (and as a result their extreme optical confinement) and their electrical controllability via gating³. Nonetheless, up to now, GPPs have not been explored for controllable generation of THz radiation.

Now, writing in *Nature Photonics*, Baicheng Yao and colleagues report they have made a significant step forward towards graphene-based THz photonic technologies⁴. The researchers have managed to generate and actively manipulate THz GPPs in graphene integrated into an



Fig. 1 | **Schematic of the graphene-based on-chip integrated device.** A heterostructure formed by two graphene (Gr) layers separated by an Al_2O_3 spacer is deposited onto a silicon nitride waveguide core. THz plasmons in graphene (GPPs) are excited by difference-frequency generation (DFG) via a counterpumped second-order nonlinearity. Electrical gating of the graphene layers via Au electrodes (yellow regions) between minimum (V_{min}) and maximum (V_{max}) voltages enables tuning of their respective Fermi levels and consequently the THz GPPs. Figure adapted from ref. ⁴, Macmillan Publishers Ltd.

on-chip dielectric waveguide. Amazingly, the generation of THz GPPs was achieved by using laser sources at near-infrared frequencies. This implies an enormous wavelength compression of THz waves, allowing for the use of the developed concept on the extreme subwavelength scale.

The THz generation happens in nonlinear media, where frequency conversion takes place. Imagine two sources (called signal and pump) emitting electromagnetic waves towards each other in a nonlinear medium. Their frequencies and momenta are denoted as $\omega_{\rm s}, k_{\rm s}$ (signal) and $\omega_{\rm p}, k_{\rm p}$ (pump), respectively. Thanks to the nonlinearity of the medium, the signal and pump waves can be converted into waves with a difference frequency, $\omega_p - \omega_s$, and sum momenta, $k_{\rm p} + k_{\rm s}$, co-propagating in the same direction as the pump. This conversion is fully consistent with both energy and momentum conservation, and in nonlinear optics is called difference-frequency generation (DFG). In Yao and colleagues' experiment, the pumping and signal laser pulses travelled along silicon nitride waveguides (1 µm in width and 725 nm height - typical singlemode dimensions for the telecom frequency

range) and were delivered to a graphene/ Al₂O₃/graphene hybrid heterostructure (Fig. 1). The latter was assembled with direct contact to the nitride core, enabling effective light-graphene interaction along the approximately 80 µm waveguide overlap. The dual-layer graphene acted as a second-order nonlinear medium and the waves resulting from DFG were synchronized in phase with propagating GPPs at THz frequencies. GPPs were clearly identified in the measured frequency spectra of the transmitted signal. Thus, graphene simultaneously played the role of both nonlinear wave convertor and plasmonic hosting medium. The wavelength of the excited GPPs (463 nm) was compressed by more than a factor of three compared with the mode wavelength in the Si₃N₄ waveguides (1,590 nm), and, remarkably, by nearly two orders of magnitude compared with the wavelength of THz radiation in free space (about 40 µm) at the GPPs' frequency (about 7 THz). Besides its technological importance, such an impressive wavelength compression and plasmonic field confinement can be explored in future fundamental studies of light-matter interaction at the nanoscale.

Although similar DFG excitation of THz GPPs in monolaver graphene has been reported before⁵, the work of Yao and co-workers was performed in a chip-scale architecture that allows for versatile GPP tunability. Indeed, apart from evidencing the on-chip excitation of deeply subwavelength THz GPPs, the researchers managed to actively control the GPPs' charge distribution and frequency. The design of the duallayer graphene heterostructure (fabricated in six steps⁴) allowed for the independent electrostatic gating (at the single-volt level) of either the top or bottom graphene layers. By varying the applied gate potentials, the researchers were able to change the corresponding Fermi levels of the layers and, consequently, the concentration of either electrons or holes, depending on the sign of the potentials. Since the GPP dispersion is precisely dictated by the Fermi level, the researchers demonstrated control over the frequency of the excited GPPs in each of the layers over a notably wide interval — an octave (4.7-9.4 THz) — limited exclusively by the optical bandwidth of the pump amplifier. Furthermore, when one of the layers was electrostatically tuned to the Dirac point, the excitation of GPPs in this layer was impeded due to the lack of charge carriers.

A special situation took place when the Fermi levels of both graphene layers became comparable as did the frequencies of the plasmons in each of the layers. In this case, due to the small separation between the layers (by 30 nm of Al_2O_3 insulator), plasmons in each of the layers could 'talk' to each other. More precisely, due to the overlap of the electromagnetic fields, the original GPPs in the dual-layer graphene hybridized into symmetric higher-frequency and antisymmetric lower-frequency modes. In the symmetric mode (also called optical plasmon mode), the charges oscillate along the graphene plane, and are thus collinear with the propagation of GPPs. In contrast, in the antisymmetric (acoustic plasmon) mode, the charges oscillate perpendicular to the graphene plane and thus to the propagation of GPPs. In the measurements of Yao et al., the optical mode was observed while the acoustic mode was strongly suppressed due to Landau damping. Interestingly, a previous experiment⁶ revealed instead acoustic (screened) THz GPPs in a graphene layer placed above an Au pad. The experimental confirmation of the coexistence of both optical and acoustic THz GPPs within the same device seems to remain a challenge.

With the help of electrical gates, Yao and colleagues demonstrate control of the THz GPPs in terms of frequency, the possibility to selectively switch them on and off in either of the graphene layers, and even to manipulate the symmetry of their charge distribution by creating hybridized GPP modes. With these capabilities for the manipulation of GPPs, there is strong potential for the developed THz GPP-based chip technology to be used in miniaturized hybrid telecom–THz circuits including, for instance, modulators and plasmon interferometers for data processing.

To fully explore the capabilities of the graphene-integrated optical chip, it would be necessary to improve the efficiency of excitation of THz GPPs. At present, the reported optimal efficiency is rather modest, approaching the value of 10⁻⁴. Roughly speaking, 10⁴ infrared photons are needed to

produce one THz GPP. The low conversion efficiency is a general problem in nonlinear processes, especially for moderate laser powers (in the work of Yao et al., the power density was approximately 2.5×10^{10} W cm⁻² for 2 ps pulses). However, there is plenty of room for improvement, such as cladding with a nonlinear bulk material (to increase the volume where the DFG takes place), or combining the structure with resonant optical antennas (to enhance and confine the electromagnetic fields). In the future, it would also be interesting to study the possibility of on-chip integration of other atomically thick van der Waals materials that support polaritons7,8. Nonlinear wave-mixing in such waveguide-integrated heterostructures may open new paths for atomic-scale optoelectronics.

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References

- 1. Tonouchi, M. Nat. Photon. 1, 97-105 (2007).
- Bonaccorso, F., Sun, Z., Hasan, T. & Ferrari, A. C. Nat. Photon. 4, 611–622 (2010).
- Grigorenko, A. N., Polini, M. & Novoselov, K. S. Nat. Photon. 6, 749–758 (2012).
- Yao, B. et al. Nat. Photon. https://doi.org/10.1038/s41566-017-0054-7 (2017).
- Constant, T. J., Hornett, S. M., Chang, D. E. & Hendry, E. Nat. Phys. 12, 124–127 (2016).
- Alonso-González, P. et al. Nat. Nanotech. 12, 31–35 (2017).
 Basov, D. N., Fogler, M. M. & García de Abajo, F. J. Science 354, aag1992 (2016).
- 8. Low, T. et al. Nat. Mater. 16, 182-194 (2017).

TERAHERTZ EMITTERS

Lasing from dressed dots

A theoretical analysis of asymmetric dressed quantum dots in a photonic crystal cavity suggests that the system could form a new type of solid-state terahertz laser. However, an experimental realization will likely require advances in fabrication technology.

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he direct generation of coherent terahertz radiation from solid-state devices is a notoriously challenging endeavour. On one side, electronics struggles with the high frequencies involved. On the other side, standard laser approaches are hindered by the lack of materials with naturally occurring terahertz dipole transitions and the problem of competing fast non-radiative relaxation processes for excited states. While terahertz quantum cascade lasers that exploit transitions between engineered sub-bands in semiconductor heterostructures are a longstanding topic of active technological development¹, their tunability and efficiency remain limited, and many efforts are exploring alternative solutions²⁻⁴. Now, another option has been brought to the table. Writing in *ACS Photonics*, Igor Chestnov and co-workers theoretically investigate the possibility of using dressed asymmetric quantum dot ensembles in a resonator to realize a terahertz laser⁵.

To understand the principle of the proposed device, one needs to first review the concepts of electromagnetically dressed states and strong light–matter coupling. When a quantum emitter is resonantly excited by a coherent pump, its energy levels