Confining light to the atomic scale

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if needed, the alignment process due to the current lateral error of 10 µm in the automated alignment) and how to ensure an environmentally controlled atmosphere during the whole process (in the current implementation some of the processes — the exfoliation of the flakes and the transfer of the assembled stack onto the final acceptor substrate — are carried out in air, which represents a serious drawback when working with air-sensitive materials). Another long-term challenge is the operating complexity of the transfer system for potential users. This issue remains to be resolved despite the effort on the authors' part to provide a comprehensive description of the set-up and even to share the software in an open repository. Indeed, the recent experience demonstrated that the success of many experimental techniques, such as the mechanical exfoliation of 2D materials, strongly relies on their ability to be easily adopted by other groups. Yet despite the remaining issues, the demonstrated robotic set-up represents an important step towards the realization of 2D-based devices with arbitrary complexity. ❐

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NANOPHOTONICS

Confining light to the atomic scale

A graphene sheet near a metal nanoantenna squeezes infrared photons into a subnanometric gap, pushing the limits of nanophotonics.

Alberto G. Curto and Jaime Gómez Rivas

The future of light-based technologies relies on the miniaturization of optical components to achieve faster, more efficient and more sensitive optoelectronic devices. It hinges on our ability to shrink light in at least one dimension while allowing it to propagate in other directions. One approach to confine photons to a scale much smaller than the free-space wavelength (λ_0) consists of forming surface plasmon-polaritons (electromagnetic waves bound to a metal–dielectric interface). However, there is a trade-off: strong spatial confinement results in shorter propagation lengths. The origin of the relation between confinement and losses is the Landau damping, the excitation by the tightly confined surface wave of electron–hole pairs in the metal that causes loss of energy stored in the plasmon. Now, writing in *Science*, Alcaraz Iranzo et al. have managed to confine light to the ultimate limit, that is, an atomically thin layer, while guiding it for hundreds of nanometres[1].

Despite the inherent limitations imposed by the Landau damping, a metal–insulator–metal nanocavity (MIM) was used as early as 2006 to compress visible light into a 3-nm-gap[2], but at the expense of it propagating for only a few oscillations. For applications requiring confinement but where propagation losses are not an issue, antenna-on-a-mirror platforms (a variant of the MIM geometry also known as patch antennas) can provide confinement to a nanometre-scale gap in localized hotspots[3].

Graphene can also sustain surface plasmon waves, now in the mid-infrared[4–6], at wavelengths around 10 µm. Through a gate voltage, the standing wave resonances associated with these propagating plasmons can be electrically tuned by changing the Fermi energy of graphene. Plasmonic resonators that exploit this effect have been made out of graphene nanoribbons, but the electric field is not confined to the one-nanometre scale and oscillations barely exist over the extent of the plasmon wavelength[7].

Following an intermediate route to confinement, Alcaraz Iranzo et al. use an antenna-on-graphene geometry. More specifically, the sample consists of a graphene layer separated by a thin dielectric spacer from metal nanoantennas with cavity sizes between 33 and 256 nm (Fig. 1). In this way, they can harness at the same time the large cross-section of metals for efficient excitation and the superior confinement of graphene plasmons. The advantage of two-dimensional (2D) materials over bulk metals is that they screen electric fields differently. They exhibit a non-local response with a strong momentum dependence of the dielectric constant. The presence of a metal near the graphene layer screens the graphene plasmons, and the gap size provides out-of-plane confinement[9].

In general, for a surface plasmon, the propagation length (L_p) quantifies the decay in the propagation direction and it is related to the imaginary part of the plasmon wavevector (k), $L_\mathrm{p} = 1/|2\mathrm{Im}(k)|$, whereas the plasmon wavelength $\lambda_\mathrm{p} = 2\pi/\mathrm{Re}(k)$ reflects the oscillation period. In a surface plasmon cavity, the resonances are at approximate cavity lengths $w = m\lambda_\mathrm{p}/2$, where m is an integer. An appropriate figure of merit for a resonator is thus the normalized propagation length $L_\mathrm{p}/\lambda_\mathrm{p}$, which gives the number of oscillations that occur before attenuation. Therefore, the number of observed resonances in a spectrum is a proxy for the confinement–propagation relation.

In the experiments of Alcaraz Iranzo et al., the appearance of higher-order Fabry–Pérot modes is a signature of confined but propagating light, to a degree not seen in previous studies of graphene plasmons. Using far-field excitation and detection in a Fourier-transform infrared spectrometer, the authors acquire extinction spectra. By turning on and off the screened graphene plasmons with a voltage and analysing the differential transmittance, they can show up

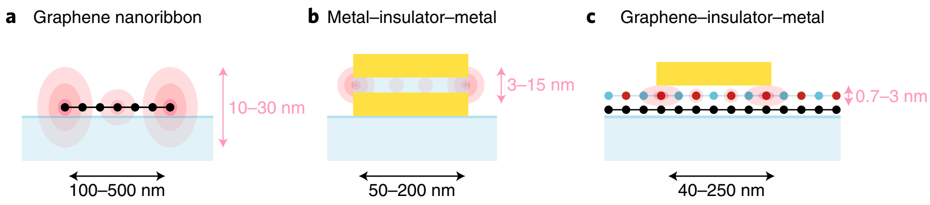

Fig. 1 | Confinement of light with graphene and metals. a–c, Light can be squeezed into different Fabry–Pérot nanocavities, such as a graphene nanoribbon (**a**), a metal–insulator–metal resonator (**b**) or a graphene–insulator–metal nanocavity formed between a gold antenna and a graphene sheet (**c**). These three types of resonators, with typical sizes indicated by the black arrows, show an increasing level of electromagnetic field confinement in the vertical direction (pink arrows). Despite the additional confinement to a smaller dielectric gap, the graphene–insulator–metal cavity can still support higher-order standing-wave resonances.

to five Fabry–Pérot resonances for a metal antenna 256-nm long and a dielectric Al_2O_3 spacer of 2 nm. For a spacer consisting of a hexagonal boron nitride monolayer with a thickness of just 0.7 nm, they observe three resonances, proving that the screened graphene plasmons can be deeply confined with a reduced increase of the losses compared to bulk materials.

In practice, the extreme confinement translates into a wavelength compression ratio of $\lambda_0/\lambda_p \approx 150$ and the possibility to reach a mode volume confinement $\lambda_0^3/V_p \approx 10^9$, where V_p is the mode volume. In the future, this could be exploited to achieve ultrastrong coupling with molecular vibrations, perhaps down to the single-molecule level, or for nanoscale quantum optics with suitable infrared quantum emitters. However, more theoretical work is needed for a complete picture of the mechanisms behind the effective reduction of Landau damping and its limits. Experimentally, even narrower gaps could be possible if the dielectric spacer is substituted by vacuum, which could result in the onset of quantum tunnelling similarly to the charge transfer in metal nanoparticle dimers[8].

These results illustrate the growing symbiosis between 2D materials and nanophotonics. Nanophotonics can enhance the interaction of light with these materials and provide a refined characterization of their complex optical properties. To date, polaritons in 2D materials have mainly focused on mid-infrared frequencies using graphene (plasmons), hexagonal boron nitride (phonons) and their heterostructures. As new and improved 2D materials become available, polaritons in other spectral regions, based on excitons in the visible and on plasmons in the terahertz, will also be used to confine light. Nanophotonic architectures could allow improved confinement of such polaritons as well. The results also bring the vision of guided wave circuits defined by antenna electrodes[9] closer to fruition.

It is remarkable that light can be confined so strongly between a metal antenna and just one layer of carbon atoms. The growing list of approaches to one-nanometre optics proves that we are entering an era of atomic-scale nanophotonic devices, where integrated photonic switches, modulators, sensors or photodetectors rely on optical modes bound to monolayer materials. When confined to the nanoscale, even the presence of a single additional atom could determine the operation of such devices. ❐

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