PHOTONICS

Stopped-light nanolasing in optical magic-angle graphene

An optical analogue of magic-angle twisted graphene bilayer gives rise to rigorously stopped light, which coupled with gain allows for a new type of a nanolaser with remarkable figures of merit.

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Place two sheets of graphene on top of each other, with the top layer slightly angled with respect to the bottom one, and a moiré pattern arises[1] — resembling, and named after, the well-known French textile design. At precisely a 'magic angle' of 1.1°, the way in which electrons move in the two coupled sheets changes: this angle condition forces the electrons to organize themselves at the same energy, creating a flat energy–momentum (E–p) dispersion band[1]. In turn, this means that the (group) velocity of the electrons, $v_g = dE/dp$, becomes zero — the electrons completely stop in their tracks, localizing at specific positions along the coupled sheets. As a result, they can now strongly interact with one another, giving rise to many exotic and unexpected phenomena, including superconductivity, correlated insulator states and orbital magnetism[2]. Now, writing in *Nature Nanotechnology*, Xin-Rui Mao and colleagues report on an optical analogue of such magic-angle graphene bilayers in an active photonic nanostructure, creating a unique type of nanolaser with highly sought-after properties[3].

Nanolasers[4] are key components under development for contemporary integrated optoelectronics and silicon photonics, fields that are poised to become gigantic in the years ahead and that have as an eventual goal to replace electrons in present-day nano-electronics with low-power-consumption and higher-bandwidth photons in nanophotonics. A crucial component in that endeavour is a compact room-temperature and power-efficient light source amenable to integration. Here, a hindrance that needs to be overcome is set by the wave nature of light itself and the associated diffraction limit, which does not allow device sizes to be much smaller than the operating wavelength of light — for example, all the way down to the desired nanoscale. One way of addressing this problem is to rely on nanometallic lasers[4] (also known as nanoplasmonic lasers or 'spasers') that exploit hybrid photon–electron excitations, allowing their size to be shrunk to dimensions much smaller than the operating wavelength. However, the use of metals usually results in excessive Joule heating, particularly if continuous (rather than pulsed) operation is desired[4].

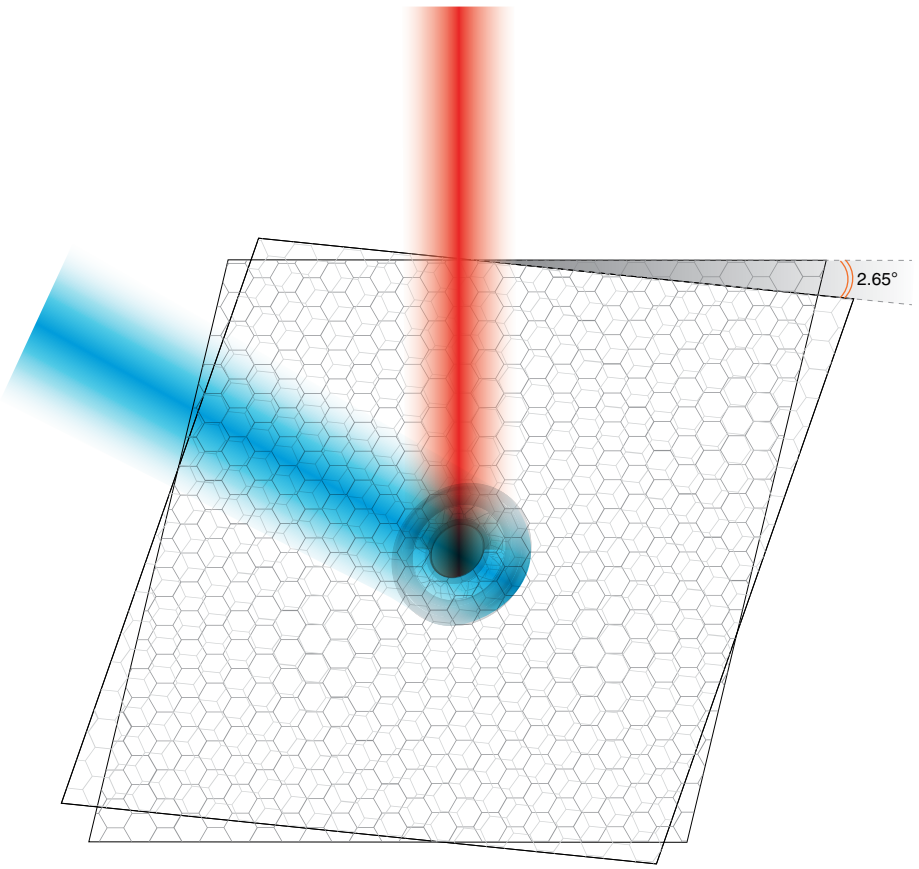

Fig. 1 | A minuscule laser in an optical analogue of a magic-angle twisted graphene bilayer. Two InGaAsP semiconductor gain media are nanostructured to form a graphene-like lattice each, and then one of them is placed on top of the other and slightly angled. The structure is designed such that when pumped by an optical beam (blue), it lases (red beam) at a wavelength that coincides with the one at which light is stopped and trapped in the structure.

A further key aspect of any laser is a cavity, used for confining light and for providing feedback: that is, for allowing light to 'experience' a laser's active gain medium multiple times, once for every round trip in the cavity, effectively increasing the gain available for light. Several nanolaser schemes have been reported over the

years. with different optical cavity designs ranging from photonic crystals to 'bound states in the continuum' (BICs, a special type of excitation that does not require a cavity) and topological lasers (immune to cavity defects and material imperfections). However, those schemes require delicate nanofabrication, or are still not very energy efficient (operation thresholds are hundreds of milliwatts, or even several watts, for BICs, and typically tens or hundreds of milliwatts for topological lasers) and/or have mode volumes considerably above a cubic wavelength.

Instead, in their work Mao and colleagues follow a completely different route, making use of dispersionless (that is, free of pulse broadening) light stopping[5,6] in optical magic-angle graphene (OMAG) lattices. They patterned a nanostructured magic-angle graphene-like lattice on two semiconductor membranes, which acted as the active gain medium, and then simply twisted the top membrane relative to the bottom by an angle precisely equal to 2.65° (Fig. 1) — slightly larger than for the electronic graphene case, owing to a stronger light coupling between the two membranes in this optical analogue. They then found that, for this angle, the coupling between the two membranes transformed the usual conical graphene dispersion (E–p) to a completely flat-band one, implying attainment of stopped and localized light ($v_g = 0$), thereby obviating the need for a cavity to localize it. This idea, the use of stopped light for lasing, was theoretically reported some time ago[7–9], but use was made therein of plasmonic or negative-refractive-index metamaterial structures, which do support stopped-light excitations but are more lossy than the design and scheme by Mao et al.[3]. Mao and colleagues, then, optically pump the OMAG laser to induce gain in the structure, and meticulously and unambiguously observe lasing at telecommunication wavelengths (around 1.5 μm).

Apart from the exceptionally innovative design concept, from a device perspective the nanolaser reported by Mao et al. exhibits exceptional performance in terms of threshold, mode volume, lasing linewidth, operating temperature, and pulsed or continuous-wave operation, compared with most recently reported alternative nanolaser designs. Specifically, first, the OMAG nanolaser has a threshold of 0.17 mW in peak pump power, which is orders of magnitude lower than topological lasers, BIC lasers or plasmonic nanolasers, and is comparable to state-of-the-art photonic crystal defect cavity lasers with the same gain materials. Concerning lasing quality factor, the OMAG nanolaser exhibits a high figure of merit of 'quality factor over mode volume' (widely used to characterize the quality of a cavity; here of the stopped-light localization) compared with all room-temperature-operated topological lasers, BIC lasers, and photonic crystal defect or plasmonic nanolasers. As regards compactness, the OMAG laser features a mode volume of just $0.01\lambda^3$ (where λ is laser wavelength), orders of magnitude lower than topological and BIC lasers, and comparable to state-of-the-art lasers based on photonic crystal defect cavities.

Finally, it is intriguing that Mao et al. do not just demonstrate an optical analogue of twisted graphene bilayers, but an optical analogue of superconductivity, too. Superconductivity was observed in electronic twisted graphene lattices a few years ago. It has been well established since the 1970s that the optical analogue of superconductivity, or of other second-order phase transitions such as ferromagnetism, is lasing — where 'order', in the form of coherent emission, spontaneously emerges from a 'disordered phase', that is, from noisy spontaneous emission. Thus, the optical analogue of superconductivity in electronic twisted graphene lattices is actually lasing in an OMAG structure — the feature that the authors of ref. [3] convincingly demonstrate.

In future work, it would be interesting to investigate whether continuous-wave electrical pumping could be attained, as well as whether the lasing threshold and mode volume could be reduced even further: for the volume, perhaps below the diffraction limit, since the scheme is cavity-free. Also interesting would be to study whether multiple lasing spots could be placed close to one another, aided again by the fact that there is no need for 'hard' in-plane material boundaries to attain localization. Apart from lasing, the enhancement of spontaneous emission rate in the stopped-light regime used by Mao et al., where the density of states and the Purcell factor increase, is potentially appealing for fast light-emitting diodes (nano-LEDs), with a goal of attaining spontaneous emission rates faster than about 50 GHz, so that LEDs could become faster than lasers[10]. And similar to the existence of unconventional superconductivity in electronic magic-angle graphene bilayers[2], it would be fascinating to examine whether unexpected optical phenomena could also arise in OMAG structures. For now, the excellent and highly sought-after device characteristics of the nanolaser demonstrated by Mao et al. help to remind us of the tangible benefits that come out of fundamental basic research, which has as its sole initial purpose to satisfy one's curiosity[1,2]. ❐

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Competing interests

The author declares no competing interests.