

OPTOMECHANICS

Diamonds take off

Nanodiamonds that are levitated by light and are equipped with internal spin provide a new platform for performing quantum and optomechanical experiments with massive, environmentally isolated objects.

Klemens Hammerer and Markus Aspelmeyer

During the past decades, experimental control over individual quantum systems has progressed to an impressive level of capability. Examples include the generation of non-classical states of an atom's motion, spatial superposition states of atoms for atom interferometry or even entanglement of the motion of different atoms¹. All of these cases exploit the optical (or microwave) coupling to intrinsic two-level quantum systems of electronic states in the atoms. Combining such two-level systems with solid-state mechanical resonators has exciting prospects, ranging from hybrid architectures for quantum information processing² to macroscopic quantum physics³. And, in fact, experiments have already demonstrated various scenarios including coherent spin manipulation in a nitrogen–vacancy (NV) colour centre in diamond⁴ and quantum control of a micromechanical resonator through a superconducting two-level system⁵, albeit with relatively short mechanical coherence times. It has been suggested that optical trapping of such solid-state systems can dramatically improve their mechanical performance^{6,7} and thus, ultimately, quantum coherence.

Now, writing in *Nature Photonics*, Neukirch *et al.*⁸ report on progress in this area with a study of trapped quantum emitters made from nanodiamond. The authors use optical tweezers to trap 100-nm-sized diamonds (containing a single-colour NV defect) at pressures down to a vacuum level of 1 kPa. Applying optical and microwave fields allowed them to control and read out both the mechanical motion and the NV spin of the nanodiamond, respectively (Fig. 1).

These results are the next step towards realizing a novel experimental platform for tests of the superposition principle, as envisioned in recent theoretical proposals^{9,10}. In principle, the approach allows unprecedented mechanical quality factors to be reached, and hence enables the motion of the centre of mass of the optically levitated nanodiamond to be

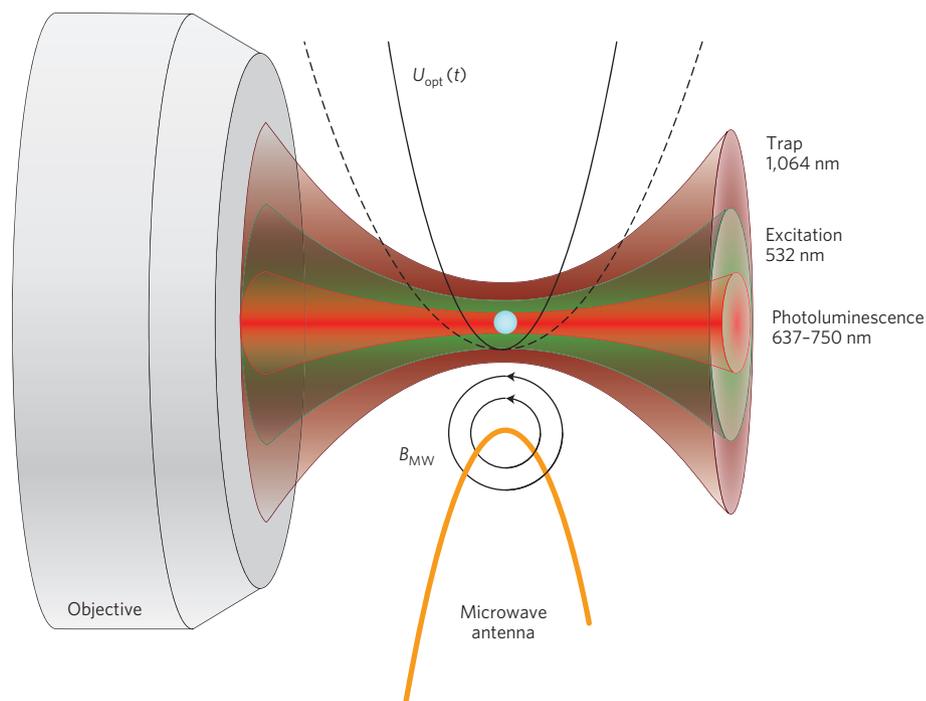


Figure 1 | A schematic diagram of an optically trapped and levitated nanodiamond. A 1,064 nm laser beam (dark red) is used to create a trap potential (U_{opt}) while a 532 nm laser beam (green) is used to excite the NV centre within the nanodiamond. Under vacuum conditions, modulation of the trap can drive the particle into motion and manipulate its spin. The magnetic field (B_{MW}) from a microwave antenna (orange) can be used to manipulate the NV centre's spin, which can be read out via measurements of photoluminescence (red).

exceedingly well isolated from motional decoherence due to the environment. Furthermore, the optical control offers a versatile means for quantum state preparation and measurement. Such a set-up has to be seen also in analogy to the powerful toolbox available for cold atoms in optical potentials, with the exciting difference that the trapped particles here have masses that are millions of times larger. Beyond performing matter wave interference experiments with large objects, optically levitated nanoparticles also offers interesting perspectives for sensing applications, due to both their exquisite isolation and measurability, and for investigations into nonequilibrium

quantum thermodynamics and statistical physics. Accordingly, optical levitation of nanoparticles has become a burgeoning field of research in the past few years. Other researchers have previously demonstrated trapping and spin control of nanodiamonds with individual NV centres in optical tweezers in a liquid¹¹ and trapping of bare silica nanospheres in a vacuum at pressures as low as 10^{-8} kPa (ref. 12). However, the work reported in the current study⁸ is the first to combine these two features in one experiment.

The authors demonstrate the versatility of their experimental set-up in several sets of data: the single emitter characteristics of the nanodiamonds and

their internal dynamics are investigated in $g^{(2)}$ -measurements of its photoluminescence, and optical detection of the electron spin monitors resonant magnetic excitation with microwave fields.

The fluctuations in the position of the nanodiamond show a transition from Brownian motion at atmospheric pressure (101 kPa) to that of a harmonically bound particle at moderate vacuum levels (~1 kPa). The corresponding mechanical quality factor of 20 is still quite low but sufficient to demonstrate parametric excitation of the particle motion up to an effective quality factor of about 1,000. Finally, manipulation of the population of the magnetic sublevels of the NV centre's triplet ground state is shown by magnetic resonance techniques. As these measurements clearly demonstrate, the experiment by Neukirch *et al.*⁸ achieves for the first time joint control over the motional and spin degrees of freedom of a levitated nanodiamond featuring a single NV centre in vacuum.

The current achievements leave plenty of room for further developments and we can expect improvements in

the near future. Most importantly, the present experiment is limited to low mechanical quality factors at a moderate vacuum level of 1 kPa. This is at present a major and not yet fully understood limitation for all existing optical trapping experiments of solid-state systems in vacuum. Significantly lower vacuum levels have thus far only been achieved with additional active feedback stabilization of the particle motion¹². To fully profit from the opportunities provided by non-tethered mechanical oscillators created by optical levitation, it will be crucial to understand and solve this problem. Additional opportunities for enhanced quantum control over both the particle and the quantum emitter may be achieved by coupling the system to an optical cavity^{6,7}. It is highly likely that experiments will soon be able to fully exploit manipulation and diagnosis of the — by then hopefully highly coherent — centre of mass motion of the nanoparticle. In any case, it is exciting to watch the growth of this new hybrid spin-mechanics platform for quantum experiments in an hitherto unexplored regime, and we look forward

to future developments in this rapidly evolving field. □

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OPTOELECTRONICS

Colour-selective photodiodes

Perovskite semiconductors have altered the landscape of solar cell research. Now researchers show that these materials may also offer a flexible platform for colour imaging and wavelength-selective sensing.

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Next time someone takes a photo of you with a smartphone or digital camera, take a moment to think about how the colour image is recorded. In most cases the image will be recorded using an array of silicon photodetectors via either charge-coupled device (CCD) or complementary metal-oxide semiconductor (CMOS)-based active pixel sensor technologies.

Silicon absorbs light with wavelengths less than ~1,100 nm, thus allowing light from the full visible spectrum to be detected. However, to produce a colour image, the photodetector elements must be able to distinguish the wavelength of the light incident on them as well. Until now this has been achieved by using red, green and blue (RGB) colour filters that mimic the spectral responses of the cone photoreceptors in the human eye. The filters are placed on top of adjacent

pixels, most commonly in the Bayer 2×2 pattern of red-green-blue-green (RGBG)¹. However, such absorptive filters add complexity to the fabrication of colour imaging arrays, make increasing pixel density challenging, and can lead to interference artefacts and poor stability when illuminated with ultraviolet light.

In this issue, Fang *et al.*² and Lin *et al.*³ independently report that colour-selective photodetectors can be fabricated without the need for filters by utilizing a new class of semiconductors. Using different architectures (Fig. 1), both groups developed photodiodes based on perovskite semiconductors, which are organic–inorganic metal halides that crystallize into a perovskite structure. These advances could lead to new designs and simplified production of colour imaging arrays. In addition, narrow-band optical detectors, such as those proposed by these

two groups, are important to a plethora of other applications that require spectral selectivity and background light suppression, such as in optical communications, biological sensing and surveillance.

Perovskite semiconductors have been the basis of remarkable developments in thin-film solar cells over the past 3 years⁴. Power conversion efficiencies of thin-film perovskite solar cells have leapt from under 10% in 2012 to more than 20% this year⁵. Other optoelectronic devices based on perovskite semiconductors have been developed subsequently, including LEDs, lasers⁶ and photodiodes^{7,8}. The perovskite materials offer two clear advantages over silicon: they are easily deposited using either solution processing or vapour deposition, and they have a remarkably high absorption coefficient, α . For example, the absorption depth of green light in silicon is $\alpha^{-1} = 1.5 \mu\text{m}$, whereas