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QUANTUM OPTICS

Quantum gates activated with laser precision

A new method enables precise control of spin qubits in diamond by selectively activating them with a laser beam, thus paving the way to the control of spin qubits in dense arrays for applications in quantum technology.

Tim Hugo Taminiau

Optically addressable spins in solids provide a promising qubit platform for quantum networks, quantum computations and quantum simulations[1–3]. A particularly fruitful approach relies on the use of individual atomic defects in wide-bandgap semiconductors, such as diamond, silicon, or silicon-carbide[1]. Such defects provide an electronic spin that can be detected, prepared, and measured using lasers and fluorescence. These electronic spins are excellent long-lived qubits with coherence times up to seconds and can be precisely manipulated using microwave pulses[4].

Larger systems can be formed by directly coupling defects through magnetic interactions over small distances (typically 20 nm) (ref. [5]) or they can be connected through long-range photon-mediated links. The latter has been achieved over distances exceeding a kilometre and makes it possible to develop quantum networks[2]. Additionally, the electron spin can be used to control nuclear spins in the surrounding solid, providing more qubits. In this way, small quantum processors with up to 10 qubits have been demonstrated[3,6]. For useful quantum computational tasks, many qubits are required to be integrated in chip-scale devices and be individually addressable. However, it is challenging to selectively control qubits in dense arrays without introducing unwanted crosstalk. The microwave pulses that are traditionally used to control spins have long wavelengths (order of 10 cm) and are difficult to focus into small volumes. Selectivity in frequency requires strong local magnetic field gradients to shift the spin frequencies, which is challenging to realize. A possible solution is to use laser light that can be focussed down to hundreds of nanometres to directly manipulate the spins[7], but resulting control fidelities are typically lower compared to microwave control.

Now, writing in *Nature Photonics*, Sekiguchi and colleagues[8] present a hybrid approach that combines the best of two worlds. They use a focussed laser beam to selectively shift the frequency of a specific spin transition, so that only a laser-illuminated qubit becomes 'activated' to a global microwave control pulse (see Fig. 1).

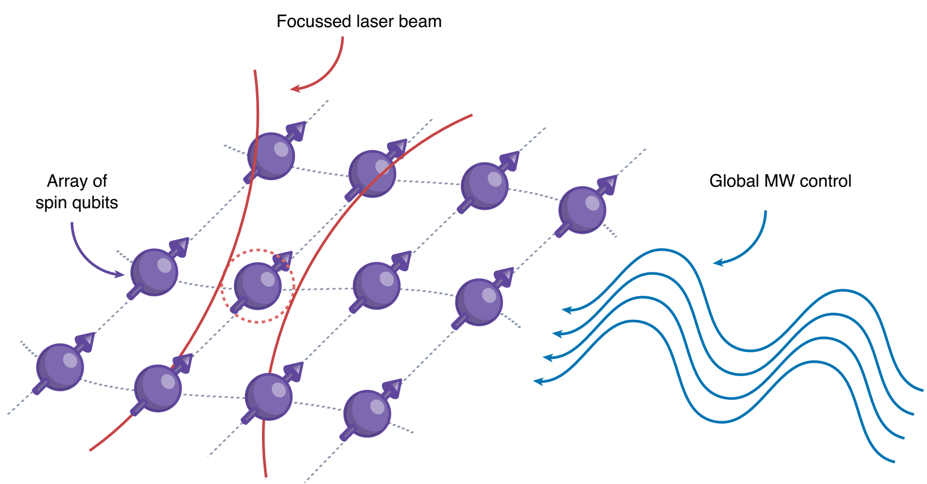

Fig. 1 | Schematic of the selective activation of a single spin qubit with a focussed laser beam. The beam (in red) is used to shift the energy levels of one of the spins (purple spheres). A global microwave field (in blue), which interacts with all the spins, is used to perform quantum gate operations. The microwave (MV) pulse is chosen in such a way that the laser-activated spin undergoes the desired evolution, while all other spins are unaffected.

When the qubit is illuminated by the laser, the microwave pulse performs the desired control operation, otherwise nothing happens.

The authors demonstrate the concept with a nitrogen vacancy (NV) defect in diamond, which consists of a substitutional nitrogen atom next to a vacancy (a missing carbon atom) and is one of the most studied spin defects for quantum technologies. The NV centre ground state forms a spin-1 system, meaning that there are three spin states available. The authors use two of these states to define their qubit. The qubit is then manipulated by microwave pulses that are (near-) resonant with transitions to the third state. By driving the spin to the third state and back, the qubit state picks up a controlled phase. Such quantum gates are sometimes called geometric or holonomic gates. The key idea for the optical activation of the gate is that the energy of the third state can be shifted by laser illumination, through the so-called Stark shift. As a result, the microwave pulse is either on resonance or detuned depending on whether the laser is on or off, so that the phase picked up by the qubit depends on the laser illumination. Importantly, the laser does not affect the qubit states directly, as it only shifts the energy of the third auxiliary state.

By combining pulses with carefully tuned frequencies, amplitudes and durations (total duration ~500 ns), the authors construct a universal gate set. The parameters are tuned so that the net evolution for an un-illuminated qubit is the identity operator; without the laser nothing happens. The authors thus realize complete and selective quantum control over the qubit. Interestingly, the design of the gates makes them robust against certain types of errors, such as overrotations of the qubit due to varying microwave field strengths. While the gate fidelities demonstrated (between 90% and 97% for different operations) still fall short of what will ultimately be needed for large-scale quantum information processing (typically larger than 99%)[9], there are several avenues for future improvement. The hybrid approach of using laser-activated microwave control already shows clear advantages over all-optical quantum gates.

Sekiguchi and colleagues also extend their control techniques to include the nitrogen-14 nuclear spin that is intrinsic to the NV centre. In particular, they demonstrate the creation of an entangled state of the NV electron spin and the ^{14}N nuclear spin. This result is significant because, besides providing an additional qubit, it also allows to exploit the extremely long coherence times of nuclear spins, which can exceed minutes[6]. Such long-lived qubits can fulfil the role of quantum memories to store quantum states in quantum networks and quantum computations.

Looking ahead, the new laser-activated quantum gates could directly improve selective control in arrays of defects with spacings on the order of the diffraction limit for the laser light (~200 nm; Fig. 1). A more challenging scenario, however, is presented by arrays with a pitch that is small enough to create a direct magnetic interaction between the spins (spacings of ~20 nm). Such dense arrays might be fabricated though ion-beam implantation with a high spatial precision in combination with high conversion factors of the implanted ions into the desired defects[10]. The direct 2-qubit gates between the spins[5] make such arrays promising systems for quantum simulations, quantum computation, and quantum sensing. The large-scale control of individual spins in arrays of hundreds, if not thousands, of coupled spins is a fascinating outstanding challenge.

Sekiguchi and colleagues hypothesize that their concepts can be combined with structured light beams to selectively control multiple qubits even with such strong couplings and small spacings. The ultimate solution for large arrays is likely to involve a combination of structured optical illumination with tailored magnetic field gradients and local electric fields, as well as spatially selective electrical detection methods[11]. For now, it is clear that the novel quantum control methods by Sekiguchi and his colleagues provide an exciting step forward and new opportunities for quantum technologies based on optically addressable spin qubits. ❐

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Competing interests

The author declares no competing interests

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OPTICAL FIBRES

3D-printing yields structured light

Optical fibres can now directly generate a variety of Bessel beams thanks to custom-designed, intricate 3D-printed structures applied to their tips.

Siddharth Ramachandran

Structured light refers to light beams that look very different from the usual visual picture that one holds of a conventional laser beam of a narrow spot with a smooth, continuous Gaussian-shaped transverse intensity profile.

For example, take the family of Bessel beams. These beams are eigensolutions of the Helmoltz equations without any paraxial approximation that typically feature oscillatory intensity patterns resembling a bullseye. As higher order solutions of propagating light fields in free space, bulk media and optical fibres, Bessel beams possess intriguing properties not typically found in conventional Gaussian beams.

A second type of interesting structured light is those whose phase or polarization-orientation varies in the transverse azimuthal direction with respect to the direction of beam propagation, yielding a beam possessing non-zero orbital angular momentum (OAM). The amount of OAM carried by a beam is dictated by its order or topological charge value which describes the level of its spiral phase twist. The combination of both of these beam types can lead to more exotic solutions such as Bessel beams that carry OAM.

Such singular beams have found varied applications on account of the fact that Bessel beams are, by their nature, diffraction resistant, as described in the seminal paper by Durnin et al[1], which has yielded fundamental implications for the field of microscopy. On the other hand, light carrying OAM does so down to the single-photon level, with implications for fields as disparate as quantum optics and telecommunications, tweezing and micromachining[2].

Given the widespread interest in structured light beams, researchers have invested considerable efforts at developing a variety of techniques, methodologies and devices to generate them. Of keen interest is to realize optical-fibre-based generation since that would enable remote delivery of such beams to environments not especially suitable for bulk devices, such as within living organisms via endoscopy, or in cold-atom chambers.

This is exactly what has been achieved by the group of Carlo Liberale at the King Abdullah University of Science and Technology (KAUST) in Saudi Arabia who have now reported the use of 3D-printed nanostructures on the tip of an optical fibre to create Bessel beams of various orders[3].

Fibre-based generation of Bessel as well as OAM beams has been accomplished before, but with limitations, in particular with respect to the order of the beam and its amount of OAM. For example, conventional long-period fibre gratings can coherently convert, with negligible losses and in an achromatic fashion, an incoming Gaussian-shaped fundamental mode of a fibre into the desired eigenmode with the preferred spatial characteristics[4]. However, these techniques have been limited by the fact that grating couplers cannot impart high values of OAM and, so