Technique could improve the sensitivity of quantum sensing devices

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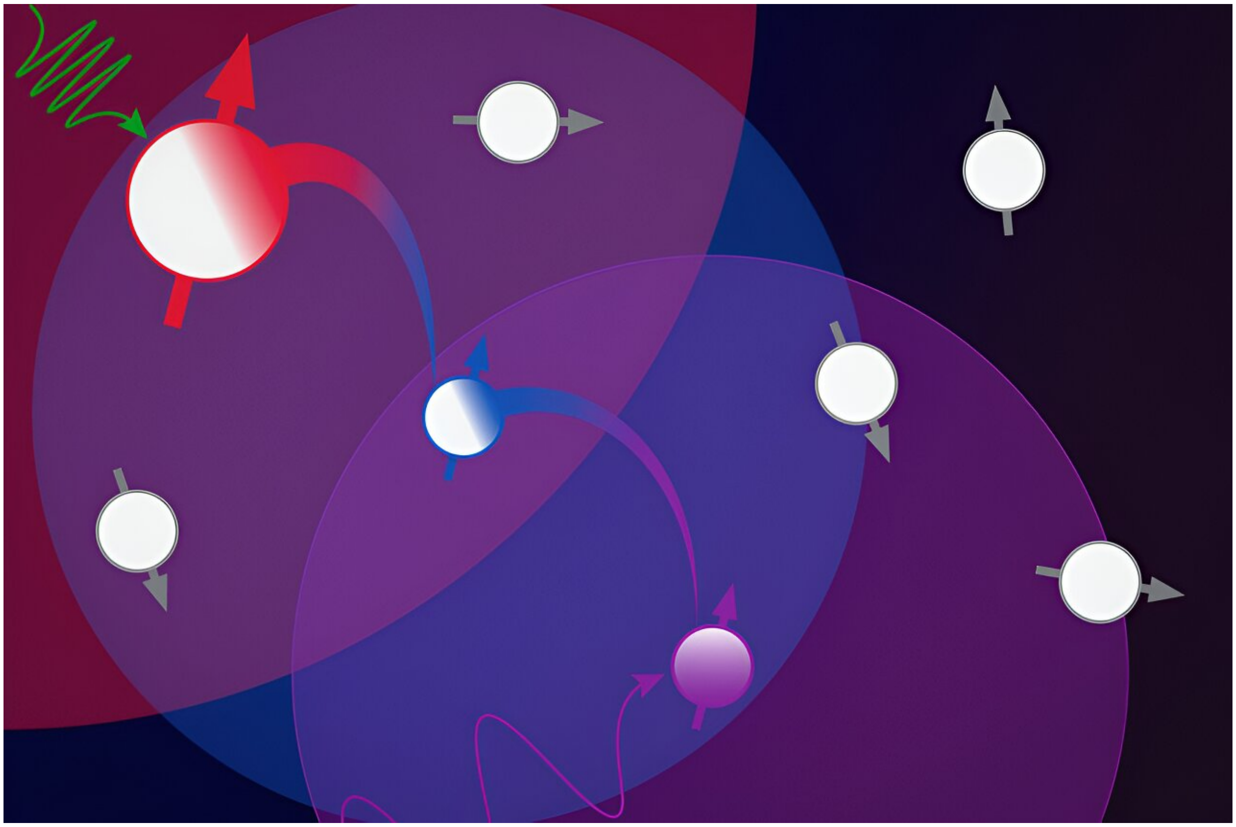

Researchers use microscopic defects inside a diamond to build a chain of three qubits (pictured as small circles with arrows) that they can use for quantum sensing. They start from a central defect, couple it with a nearby defect, and then use this second defect to find and control a third defect. Credit: Massachusetts Institute of Technology

In quantum sensing, atomic-scale quantum systems are used to measure electromagnetic fields, as well as properties like rotation, acceleration, and distance, far more precisely than classical sensors can. The technology could enable devices that image the brain with unprecedented detail, for example, or air traffic control systems with precise positioning accuracy.

As many real-world quantum sensing devices are emerging, one promising direction is the use of microscopic defects inside diamonds to create "qubits" that can be used for quantum sensing. Qubits are the building blocks of quantum devices.

Researchers at MIT and elsewhere have developed a technique that enables them to identify and control a greater number of these microscopic defects. This could help them build a larger system of qubits that can perform quantum sensing with greater sensitivity.

Their method builds off a central defect inside a diamond, known as a nitrogen-vacancy (NV) center, which scientists can detect and excite using laser light and then control with microwave pulses. This new approach uses a specific protocol of microwave pulses to identify and extend that control to additional defects that can't be seen with a laser, which are called dark spins.

The researchers seek to control larger numbers of dark spins by locating them through a network of connected spins. Starting from this central NV spin, the researchers build this chain by coupling the NV spin to a nearby dark spin, and then use this dark spin as a probe to find and control a more distant spin which can't be sensed by the NV directly. The process can be repeated on these more distant spins to control longer chains.

"One lesson I learned from this work is that searching in the dark may be quite discouraging when you don't see results, but we were able to take this risk. It is possible, with some courage, to search in places that people haven't looked before and find potentially more advantageous qubits," says Alex Ungar.

A Ph.D. student in electrical engineering and computer science and a member of the Quantum Engineering Group at MIT, Ungar is lead author of a paper on this technique, which was published Feb. 7 in *PRX Quantum*.

His co-authors include his advisor and corresponding author, Paola Cappellaro, the Ford Professor of Engineering in the Department of Nuclear Science and Engineering and professor of physics; as well as Alexandre Cooper, a senior research scientist at the University of Waterloo's Institute for Quantum Computing; and Won Kyu Calvin Sun, a former researcher in Cappellaro's group who is now a postdoc at the University of Illinois at Urbana-Champaign.

Diamond defects

To create NV centers, scientists implant nitrogen into a sample of diamond.

But introducing nitrogen into the diamond creates other types of atomic defects in the surrounding environment. Some of these defects, including the NV center, can host what are known as electronic spins, which originate from the valence electrons around the site of the defect. Valence electrons are those in the outermost shell of an atom. A defect's interaction with an external magnetic field can be used to form a qubit.

Researchers can harness these electronic spins from neighboring defects to create more qubits around a single NV center. This larger collection of qubits is known as a quantum register. Having a larger quantum register boosts the performance of a quantum sensor.

Some of these electronic spin defects are connected to the NV center through magnetic interaction. In past work, researchers used this interaction to identify and control nearby spins. However, this approach is limited because the NV center is only stable for a short amount of time, a principle called coherence. It can only be used to control the few spins that can be reached within this coherence limit.

In this new paper, the researchers use an electronic spin defect that is near the NV center as a probe to find and control an additional spin, creating a chain of three qubits.

They use a technique known as spin echo double resonance (SEDOR), which involves a series of microwave pulses that decouple an NV center from all electronic spins that are interacting with it. Then, they selectively apply another microwave pulse to pair the NV center with one nearby spin.

Unlike the NV, these neighboring dark spins can't be excited, or polarized, with laser light. This polarization is a required step to control them with microwaves.

Once the researchers find and characterize a first-layer spin, they can transfer the NV's polarization to this first-layer spin through the magnetic interaction by applying microwaves to both spins simultaneously. Then once the first-layer spin is polarized, they repeat the SEDOR process on the first-layer spin, using it as a probe to identify a second-layer spin that is interacting with it.

Controlling a chain of dark spins

This repeated SEDOR process allows the researchers to detect and characterize a new, distinct defect located outside the coherence limit of the NV center. To control this more distant spin, they carefully apply a specific series of microwave pulses that enable them to transfer the polarization from the NV center along the chain to this second-layer spin.

"This is setting the stage for building larger quantum registers to higher-layer spins or longer spin chains, and also showing that we can find these new defects that weren't discovered before by scaling up this technique," Ungar says.

To control a spin, the microwave pulses must be very close to the resonance frequency of that spin. Tiny drifts in the experimental setup, due to temperature or vibrations, can throw off the microwave pulses.

The researchers were able to optimize their protocol for sending precise microwave pulses, which enabled them to effectively identify and control second-layer spins, Ungar says.

"We are searching for something in the unknown, but at the same time, the environment might not be stable, so you don't know if what you are finding is just noise. Once you start seeing promising things, you can put all your best effort in that one direction. But before you arrive there, it is a leap of faith," Cappellaro says.

While they were able to effectively demonstrate a three-spin chain, the researchers estimate they could scale their method to a fifth layer using their current protocol, which could provide access to hundreds of potential qubits. With further optimization, they may be able to scale up to more than 10 layers.

In the future, they plan to continue enhancing their technique to efficiently characterize and probe other electronic spins in the environment and explore different types of defects that could be used to form qubits.

More information: Alexander Ungar et al, Control of an Environmental Spin Defect beyond the Coherence Limit of a Central Spin, *PRX Quantum* (2024). DOI: 10.1103/PRXQuantum.5.010321

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