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It is a quantum fractal algorithmic universe

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Sound Drives 'Quantum Jumps' Between Electron Orbits

Cornell researchers have demonstrated that acoustic sound waves can be used to control the motion of an electron as it orbits a lattice defect in a diamond, a technique that can potentially improve the sensitivity of quantum sensors and be used in other quantum devices.

Sound waves – artistic impression. Image credit: Copilot Designer / Alius Noreika

Advances in quantum information technology require finding new ways to control electrons and other microscopic particles. In "Coherent Acoustic Control of Defect Orbital States in the Strong-Driving Limit," Gregory Fuchs, professor of applied and engineering physics, and his postdoctoral associate, Brendan McCullian, collaborated with Erich Mueller, professor of physics in the College of Arts and Sciences, and his doctoral student, Vaibhav Sharma, to engineer a setting where sound waves can drive 'quantum jumps' between electron orbits. The work was published Aug. 19 in the journal PRX Quantum.

McCullian built a microscopic speaker on the surface of a diamond chip, which operated at a frequency that exactly matched an electronic transition. Using techniques similar to those employed in magnetic resonance imaging, he was able to demonstrate coherent control of a single electron inside the diamond chip.

Qubits – the quantum analog of the bits found in a classical computer – must remain coherent, or in a stable state, in order to do something useful. This coherence is very fragile and is easily lost by fluctuations of the environment, such as when a nearby electron jumps from one location to another. For many years scientists have extended qubit coherence times by using a technique called spin resonance, which uses microwaves and magnetic fields to alter the electron behavior. Fuchs and his group attempted to extend this technique to the acoustic domain and improve the coherence of the orbitals.

"We acoustically drove the orbital states in a way that's somewhat analogous to the spin resonance, and then used the established toolbox of spin resonance techniques to investigate the coherence of that orbital state," said Fuchs. "It was very interesting to us that we could do an orbital version of spin resonance: take those tools that we know from spin resonance – for example, coherent control and Rabi oscillations – and with a couple-gigahertz acoustic resonator, map that onto the orbital states and see that those techniques are still valid."

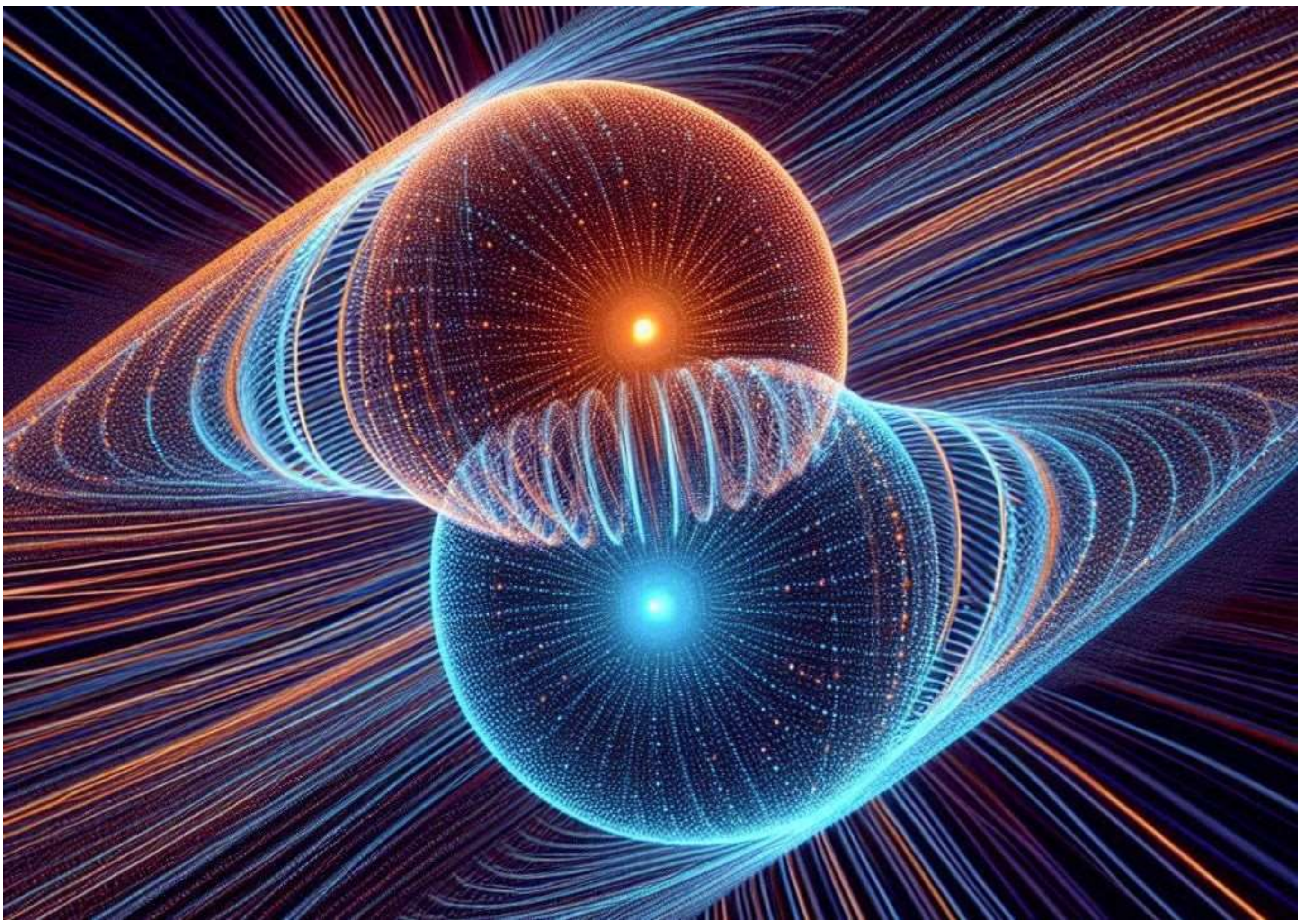
Fuchs's work helps advance knowledge of the nitrogen-vacancy (NV) center, a defect in diamond crystal lattices that is an important qubit for sensing and quantum networking, and helps develop new tools to combat environmental fluctuations that lead to spectral diffusion, which can cause major problems in quantum networking applications that rely on a steady optical transition where the frequency of every emitted photon is the same.

"By investigating how the NV center interacts with these noise sources and finding ways to modify that interaction using tools that we normally reserve for spins, we've figured out a way that we can make it work with the orbital states. That is an important addition to science," said Fuchs. "This project was also an example of the way collaboration between teams should work. The experimental techniques were developed in my lab, but then we collaborated with a group in the Department of Physics that provided a theoretical analysis and helped us frame our predictions and understanding of the results."

“It was a hugely rewarding collaboration,” said Mueller. “The acoustic waves excited the electrons through a mechanism similar to how one ‘pumps’ on a playground swing. When the vibrations are in sync with the electron motion they can transfer energy to it. It is truly amazing that one can control the electron motion with what is essentially a loud-speaker.”

‘Quantum Coherence’ Survives In Ultracold Molecules

Scientists are hot on the trail of a process called quantum coherence, the ability of particles to maintain phase relationships and exist in multiple states simultaneously. It’s akin to the parts of a wave being synchronized. However, whether quantum coherence can persist through a chemical reaction, where bonds break and form, has been questioned.



A stylized computer-generated illustration suggesting the phenomenon of quantum coherence between two particles. Image Credit: Alius Noreika / Copilot Designer

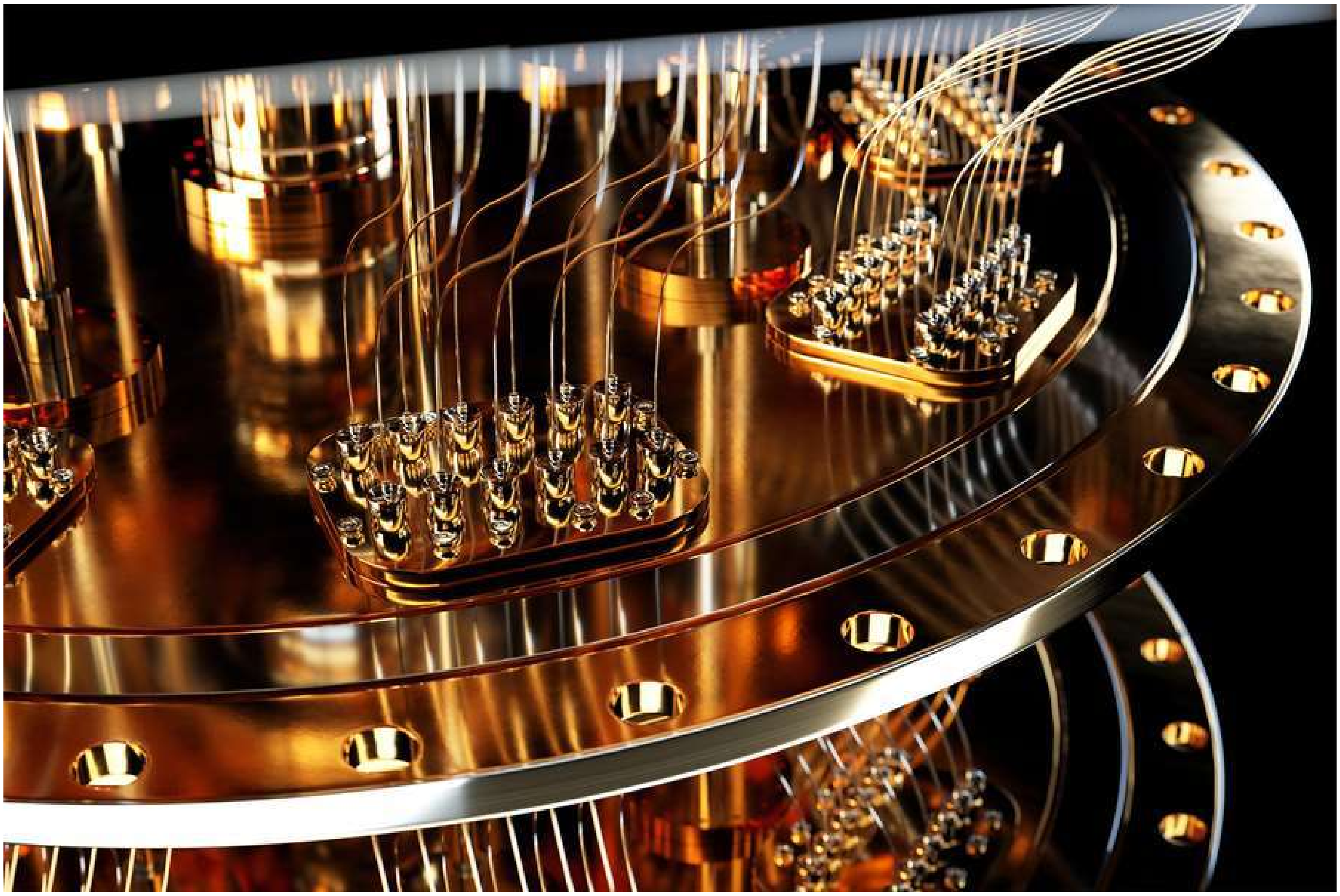
Scientists have demonstrated that quantum coherence can survive in a chemical reaction with ultracold molecules. Researchers’ findings highlight the potential of harnessing chemical reactions for applications in quantum information science. The work was published in the journal *Science* and funded by the U.S. National Science Foundation.

Scientists are using sophisticated laser techniques to research quantum entanglement between the states of a chemical reaction. Quantum entanglement is a key concept at the heart of quantum information science, whereby two particles can occupy a shared quantum state.

“Our findings precede the study of coherence in reactions under wet and warm conditions, which may be of interest for a wide range of chemical phenomena, including in the brain,” write Kang-Kuen Ni of Harvard University and co-authors.

Toward A Code-Breaking Quantum Computer

The most recent email you sent was likely encrypted using a tried-and-true method that relies on the idea that even the fastest computer would be unable to break a gigantic number into factors efficiently.



Quantum computer. Image credit: MIT

Quantum computers, on the other hand, promise to rapidly crack complex cryptographic systems that a classical computer might never be able to unravel. This promise is based on a quantum factoring algorithm proposed in 1994 by Peter Shor, who is now a professor at MIT.

But while researchers have taken great strides in the last 30 years, scientists have yet to build a quantum computer powerful enough to run Shor's algorithm.

As some researchers work to build larger quantum computers, others have been trying to improve Shor's algorithm so it could run on a smaller quantum circuit. About a year ago, New York University computer scientist Oded Regev proposed a major theoretical improvement. His algorithm could run faster, but the circuit would require more memory.

Building off those results, MIT researchers have proposed a best-of-both-worlds approach that combines the speed of Regev's algorithm with the memory-efficiency of Shor's. This new algorithm is as fast as Regev's, requires fewer quantum building blocks known as qubits, and has a higher tolerance to quantum noise, which could make it more feasible to implement in practice.

In the long run, this new algorithm could inform the development of novel encryption methods that can withstand the code-breaking power of quantum computers.

"If large-scale quantum computers ever get built, then factoring is toast and we have to find something else to use for cryptography. But how real is this threat? Can we make quantum factoring practical? Our work could potentially bring us one step closer to a practical implementation," says Vinod Vaikuntanathan, the Ford Foundation Professor of Engineering, a member of the Computer Science and Artificial Intelligence Laboratory (CSAIL), and senior author of a paper describing the algorithm.

The paper's lead author is Seyoon Ragavan, a graduate student in the MIT Department of Electrical Engineering and Computer Science. The research will be presented at the 2024 International Cryptology Conference.

Cracking cryptography

To securely transmit messages over the internet, service providers like email clients and messaging apps typically rely on RSA, an encryption scheme invented by MIT researchers Ron Rivest, Adi Shamir, and Leonard Adleman in the 1970s (hence the name "RSA"). The system is based on the idea that factoring a 2,048-bit integer (a number with 617 digits) is too hard for a computer to do in a reasonable amount of time.

That idea was flipped on its head in 1994 when Shor, then working at Bell Labs, introduced an algorithm which proved that a quantum computer could factor quickly enough to break RSA cryptography.

"That was a turning point. But in 1994, nobody knew how to build a large enough quantum computer. And we're still pretty far from there. Some people wonder if they will ever be built," says Vaikuntanathan.

It is estimated that a quantum computer would need about 20 million qubits to run Shor's algorithm. Right now, the largest quantum computers have around 1,100 qubits.

A quantum computer performs computations using quantum circuits, just like a classical computer uses classical circuits. Each quantum circuit is composed of a series of operations known as quantum gates. These quantum gates utilize qubits, which are the smallest building blocks of a quantum computer, to perform calculations.

But quantum gates introduce noise, so having fewer gates would improve a machine's performance. Researchers have been striving to enhance Shor's algorithm so it could be run on a smaller circuit with fewer quantum gates.

That is precisely what Regev did with the circuit he proposed a year ago.

"That was big news because it was the first real improvement to Shor's circuit from 1994," Vaikuntanathan says.

The quantum circuit Shor proposed has a size proportional to the square of the number being factored. That means if one were to factor a 2,048-bit integer, the circuit would need millions of gates.

Regev's circuit requires significantly fewer quantum gates, but it needs many more qubits to provide enough memory. This presents a new problem.

"In a sense, some types of qubits are like apples or oranges. If you keep them around, they decay over time. You want to minimize the number of qubits you need to keep around," explains Vaikuntanathan.

He heard Regev speak about his results at a workshop last August. At the end of his talk, Regev posed a question: Could someone improve his circuit so it needs fewer qubits? Vaikuntanathan and Ragavan took up that question.

Quantum ping-pong

To factor a very large number, a quantum circuit would need to run many times, performing operations that involve computing powers, like 2 to the power of 100.

But computing such large powers is costly and difficult to perform on a quantum computer, since quantum computers can only perform reversible operations. Squaring a number is not a reversible operation, so each time a number is squared, more quantum memory must be added to compute the next square.

The MIT researchers found a clever way to compute exponents using a series of Fibonacci numbers that requires simple multiplication, which is reversible, rather than squaring. Their method needs just two quantum memory units to compute any exponent.

"It is kind of like a ping-pong game, where we start with a number and then bounce back and forth, multiplying between two quantum memory registers," Vaikuntanathan adds.

They also tackled the challenge of error correction. The circuits proposed by Shor and Regev require every quantum operation to be correct for their algorithm to work, Vaikuntanathan says. But error-free quantum gates would be infeasible on a real machine.

They overcame this problem using a technique to filter out corrupt results and only process the right ones.

The end-result is a circuit that is significantly more memory-efficient. Plus, their error correction technique would make the algorithm more practical to deploy.

“The authors resolve the two most important bottlenecks in the earlier quantum factoring algorithm. Although still not immediately practical, their work brings quantum factoring algorithms closer to reality,” adds Regev.

In the future, the researchers hope to make their algorithm even more efficient and, someday, use it to test factoring on a real quantum circuit.

“The elephant-in-the-room question after this work is: Does it actually bring us closer to breaking RSA cryptography? That is not clear just yet; these improvements currently only kick in when the integers are much larger than 2,048 bits. Can we push this algorithm and make it more feasible than Shor’s even for 2,048-bit integers?” says Ragavan.

Nebraska-Jackson State Project To Grow Opportunities In Quantum Sensing

Abdelghani Laraoui, assistant professor of mechanical and materials engineering, is collaborating with faculty from Jackson State University, a historically Black college in Mississippi, on a three-year, $800,000 project to help train dozens of African-American youth while developing America's expertise in quantum sensing.

Since The project, Collaboration on Quantum Sensing Research and Education for Minority Participants, is funded through the National Science Foundation Expanding Capacity in Quantum Information Science and Engineering, or ExpandQISE, program.

The project is launching in October, and will mentor 80 graduate, undergraduate and K-12 minority participants from Jackson State, nearby community colleges and K-12 schools during its three-year term. The goal is to provide comprehensive training in quantum biosensing through QISE coursework and use of diamond quantum microscopy — a specialty of Laraoui, who is a research group leader with Nebraska EPSCoR's EQUATE collaboration on quantum materials science.

Specifically, this research focuses on the development and application of quantum sensing technology by using nitrogen vacancy centers in diamond for real time monitoring of cytochrome-c release during cell apoptosis. The long-term outcome of this research is to establish scientific design criteria for quantum material-based multifunction compatible sensors for in vivo imaging of cytochrome-c — a fundamental advance for quantum information technologies.

This Nebraska-Mississippi project aims to:

- Improve research infrastructure in quantum sensing capability at JSU by developing diamond quantum microscope,
- Develop collaborative MS/PhD advising program for underrepresented students with a strong focus on quantum sensing,
- Initiate summer research for undergraduates program at Jackson State for underrepresented participants in QISE research and education,
- Builds quantum information science and engineering research and education program for K-12 participants, and

- Design a new quantum information science and engineering course with an emphasis on the hands-on and project-based learning modules.

As an HBCU and the only urban university in Mississippi, Jackson State has a unique opportunity to attract and retain Black students in quantum information science and engineering research and education. African Americans represent 98 percent of the minority population in Mississippi and 37% of the state's citizens, giving it the highest concentration per capita of this minority group in the nation.

This project is co-funded by NSF's Historically Black Colleges and Universities Undergraduate Program, which provides awards to strengthen undergraduate education and research in science, technology, engineering, and math at HBCUs. This award was jointly funded by NSF's Directorate for Engineering; Division of Civil, Mechanical and Manufacturing Innovation; NSF's Directorate for Mathematical and Physical Sciences; and NSF's Office of Strategic Initiatives, which includes EPSCoR (Established Program to Stimulate Competitive Research) projects to promote geographic diversity in STEM funding.

World’s First Micromachine Twists 2d Materials At Will

Just a few years ago, researchers discovered that changing the angle between two layers of graphene, an atom-thick sheet of carbon, also changed the material’s electronic and optical properties. They then learned that a “twist” of 1.1 degrees — dubbed the “magic” angle — could transform this metallic material into an insulator or a superconductor, a finding that ignited excitement about a possible pathway to new quantum technologies.

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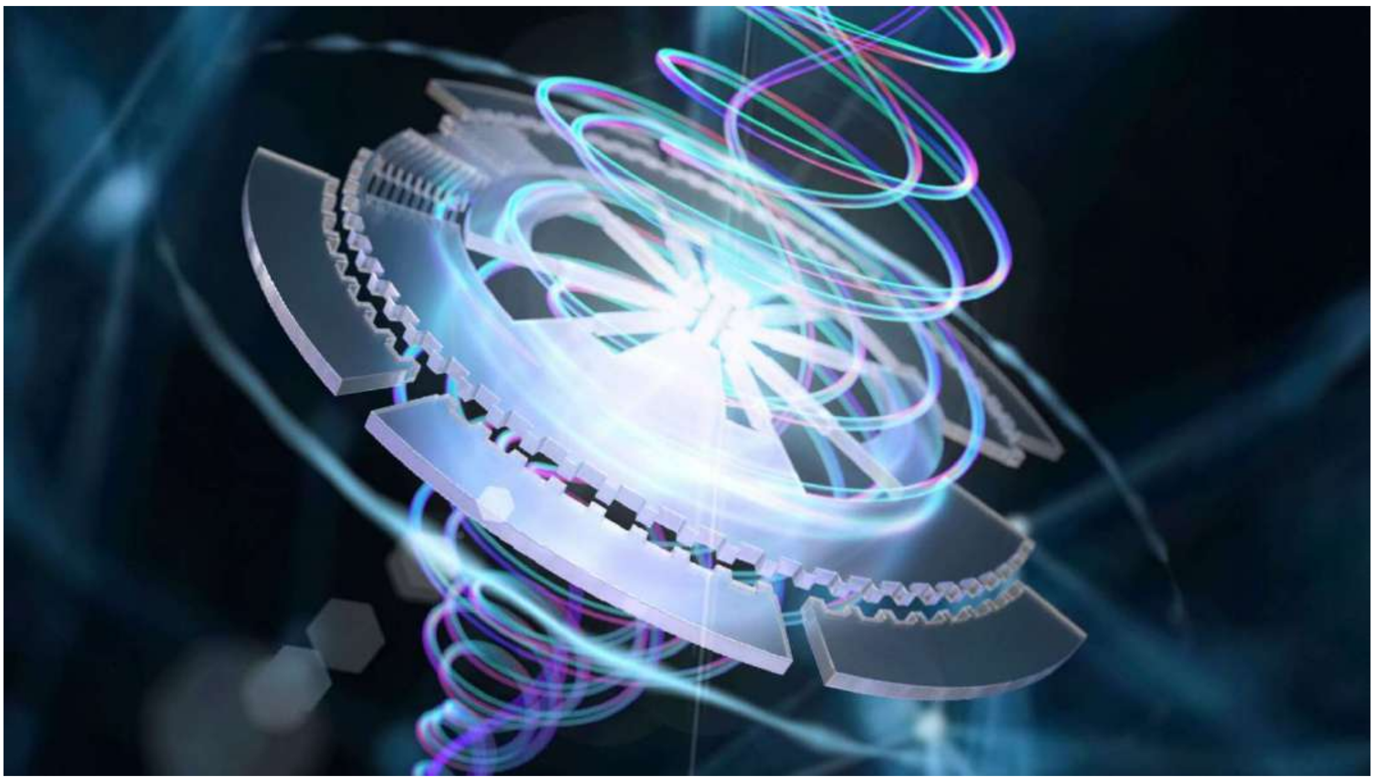

Twisting light with a micromachine. Image credit: Yuan Cao

To study the physics underlying this phenomenon, “twistronics” researchers had to produce tens to hundreds of different configurations of the twisted graphene structures — a costly and labor-intensive process. But a team of researchers led by Yuan Cao, the leading discoverer of the magic angle in 2018 and now an assistant professor of electrical engineering and computer sciences at UC Berkeley, has created a device that can twist a single structure in countless ways.

In a study published in Nature, the researchers demonstrated the world's first micromachine that can twist 2D materials at will. The fingernail-sized, on-chip platform, called MEGA2D, uses microelectromechanical systems (MEMS) to conduct voltage-controlled manipulation of 2D materials — which are only nanometers thick — with unprecedented flexibility and precision.

"Our work extends the capabilities of existing technologies in manipulating low-dimensional quantum materials," said Cao. "It also paves the way for novel hybrid 2D and 3D structures, with promising implications in condensed-matter physics, quantum optics and related fields."

A single structure, numerous configurations

Using the ultra-tunable MEGA2D technology, Cao and his team demonstrated multiple, exotic properties in a single structure made of two pieces of hexagonal boron nitride (a close relative of graphene). Moreover, they required only a handful of samples to study the structure's nonlinear optical properties and measure the Van der Waals force.

One finding, however, surprised the researchers. They noticed "swirls" in the nonlinear optical properties of hexagonal boron nitride when twisted by MEGA2D.

"The swirls resemble 'half-skyrmions' — a type of topological quasiparticle found in some magnetic materials but was never thought of in nonlinear optical systems," said Haoning Tang, lead author of the paper and a postdoc at Harvard University. "These nonlinear optical properties were not discussed before and would not have been found without the active tuning platform MEGA2D."

Twisting and tuning

According to the researchers, the MEGA2D platform has several potential applications beyond twistronics, including use as a tunable light source for classic, or standard, light bulbs as well as for quantum versions. The latter are special light sources that use nonlinear optics to convert blue light to red light and are useful for quantum computing using photons.

"Traditionally, these quantum light sources have fixed polarizations, the way light waves oscillate in the space," said Tang. "With our MEGA2D device, the light source outputs a beam with tunable polarization, and the tuning range is very broad. One highlight is that it can directly generate so-called circular polarized light, which is light that oscillates in a rotating manner and carries angular momentum."

For now, the team believes that the true power of the MEGA2D technology lies in fundamental research. Cao points out that humankind is still limited in some ways by what we can see and understand about nature.

“By having this new ‘knob’ via our MEGA2D technology, we envision that many underlying puzzles in twisted graphene and other Van der Waals materials could be resolved easily,” said Cao. “It will certainly also bring other new discoveries along the way.”

A collaborative effort

According to Cao, persistence and collaboration were key to the successful development of MEGA2D technology. Tang is largely credited for designing the MEGA platform and for realizing the vision of using MEMS technology to control 2D interfaces in real time.

“This is really teamwork that substantially benefited from a mixed expertise of physics, engineering — and a lot of tinkering and fun!” said Cao.

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