microscope to see the checkerboard pattern directly, that option wasn't available to the USTC researchers. Instead, they used Bragg scattering to measure the spin ordering in their 3D lattice, similar to how x-ray scattering probes the ordering of atoms in a real crystal.

Figure 2 shows one of their experiments that studied the antiferromagnetic phase transition. Panel a is a sketch of the system's phase diagram in terms of entropy (related to temperature) and the particle density n; the antiferromagnetic phase forms a symmetric dome on either side of the half-filled state $n = 1$. The series of blue dots shows how the researchers tuned n to probe a slice of phase space that cuts through the antiferromagnetic dome.

Panel b shows the USTC researchers' measurements of the spin structure factor S, which quantifies how well-ordered the spins are. Near $n = 1$, S is large, as expected of an antiferromagnetic phase. But outside of the phase boundaries, which the researchers estimate to lie somewhere in the gray bands, S doesn't abruptly drop to zero. Rather, it tails off with a power-law dependence.

The power law is defined by a critical exponent, and there are only a few values the exponent could plausibly take. A wide variety of seemingly disparate physical systems fall into a small number of universality classes, each with its own characteristic scaling behavior (see PHYSICS TODAY, July 2023, page 14). The FHM is thought to belong to the same universality class as the 3D Heisenberg model, which would give it a critical exponent of 1.396. But that's never been confirmed, because the FHM phase transition had never been observed before.

When the researchers drew a line with slope −1.396, they found that it agreed reasonably well with their data in the log–log plot in figure 2b. Importantly, though, the experiment doesn't constitute a measurement of the critical exponent. "Accurately determining the critical exponent of a power-law function requires making measurements over several orders of magnitude," explains Yao. "In our current work, we did not fulfill that condition. But in the future, we hope to determine the value precisely."

Your move

Pan, Chen, Yao, and colleagues have performed the most quantitative and informative FHM experiment to date, but there's much more to be done. The superconducting phase, if it exists, lies at temperatures even lower than the researchers have achieved, and they'll need further experimental improvements to access it.

If and when researchers do reach the superconducting phase, the next step will be to perform detailed experiments to try to uncover the mechanism by which the fermionic particles combine into bosonic pairs that condense into a superfluid. Part of the reason that cuprate superconductivity has been so enigmatic is that there's no way to tune individual properties in isolation. Just to change the charge-carrier density, for example, it's necessary to make a new sample with a different chemical composition, which changes other properties in tandem.

In the FHM, on the other hand, changing the particle density is as straightforward as reloading the lattice with more or fewer atoms. Other parameters can be tuned too, including those that take the model beyond the classic FHM to simulate effects such as phonons or spin fluctuations. By testing how each parameter does or doesn't contribute to superconductivity, researchers could finally uncover the mysterious electron-pairing mechanism.

But understanding superconductivity isn't the only goal. Strongly correlated electron systems give rise to many other physical phenomena, some of which show up in the FHM at the temperatures researchers can achieve already. "Due to the difficulty in numerical calculations, little is currently known about the 3D FHM at low temperatures and away from half filling," says Yao. "Mapping out its phase diagram is important in its own right."

And the USTC group won't be the only one working on the FHM. Box traps, the key to lowering the quantum gas's entropy and temperature, are an established technology, so now that their importance for creating low-entropy gases is known, other groups can start using them too. The diffractive optical elements used to create the flat-top beams were custom designed, but similar products are available commercially. "It will absolutely be possible for other groups to replicate these results," says Hulet. "Pan's group is ahead of everybody else, but only by a few months."

Johanna Miller

References

1. H.-J. Shao et al., *Nature* **632**, 267 (2024).
2. A. Mazurenko et al., *Nature* **545**, 462 (2017).

A titanium:sapphire laser on a chip

The miniaturized laser has a lowered output power suited for many applications without sacrificing stability and tunability.

A standard tool in optics labs, titanium-doped sapphire lasers are valued for their ability to be precisely tuned across a wide wavelength range. In Stanford University's Nanoscale and Quantum Photonics Lab, led by Jelena Vučković, researchers use tabletop Ti:sapphire lasers to excite artificial atoms in solid-state quantum optics experiments.

But the lasers typically require a bulky, expensive, high-power pump laser. And the Vučković group, like many others, require only a fraction of the Ti:sapphire's output power: The researchers in the Nanoscale and Quantum Photonics Lab often end up attenuating the laser from watts to microwatts.

Dissatisfied with the standard laser setup's wasted power, high cost, and other shortcomings, the Stanford researchers saw an opportunity to miniaturize. Vučković is no stranger to shrinking lab components: She and members of her team had previously collaborated on the construction of a particle accelerator on a chip.[1]

Taking advantage of recent improvements in integrated photonics, the team has now scaled down the laser to an on-chip platform in which the light passes through a waveguide amplifier fabricated from a Ti:sapphire film.[2] Although it is only a first iteration, the smaller laser is a better match to the power, stability, and tunability needs of Vučković's lab and presumably those of many others.

Why Ti:sapphire?

Developed in the 1980s, Ti:sapphire lasers are solid-state lasers that can operated in continuous or pulsed mode. A high-power pump laser—the 10 kg one in Vučković's lab costs around \$100 000—is directed through a crystal of Ti:sapphire, which serves as the gain medium. A pump laser of sufficient power excites the Ti atoms to generate lasing at a different, longer wavelength.

Sapphire doped with Ti^{3+} ions has the largest gain bandwidth of any laser crystal, which allows for a broad wavelength-tuning range of 650–1100 nm and the generation of pulses as short as 5 fs. In their pulsed mode, Ti:sapphire lasers reach powers that are 100 times as great as those of dye lasers. The laser's combination of flexibility and power has been crucial for advancements in two-photon microscopy and optical frequency combs.

Previous attempts to scale down Ti:sapphire lasers have been only partially successful. In 2023, researchers at Yale University bonded Ti:sapphire material onto a silicon nitride photonic chip, but only a small portion of the optical field was inside the gain material. That partial overlap led to higher lasing thresholds and milliwatt output powers that are not well matched for many common experimental needs. Moreover, the lasers were not designed to be tunable, which severely limited their potential applications.[3]

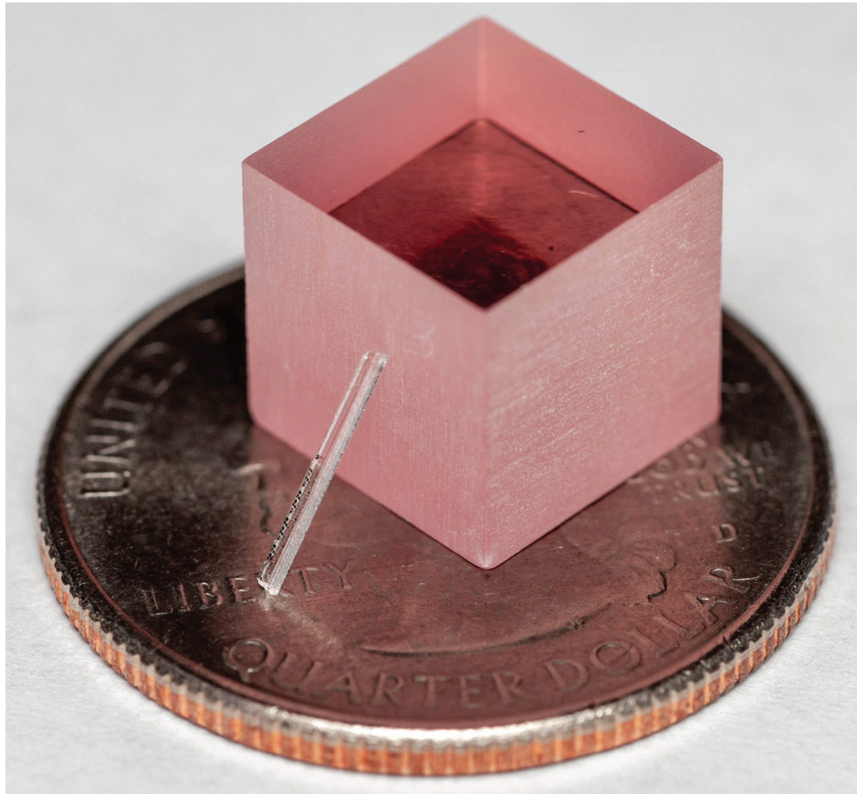

FIGURE 1. A SAPPHIRE ROD holds a whole array of mini lasers, seen here leaning against a titanium:sapphire block. The mini lasers, each with up to milliwatt output power, are better for applications that require simultaneous control of many emitters at disparate frequencies. (Adapted from ref 1.)

Integrating photonics

The device developed by Vučković's group is built on a thin-film monocrystalline sapphire-on-insulator photonics platform. High-quality crystalline Ti:sapphire isn't easily grown in a thin, uniform layer atop anything other than sapphire. Growth on a different material results in a lattice mismatch, and the imperfections in the crystalline structure prevent the attainment of the desired laser properties. So instead, the Stanford researchers start with a bulk material: a uniform wafer of approximately 0.5-mm-thick Ti:sapphire. The wafer is bonded to the sapphire (the translucent rod seen in figure 1) using silica as a glue before the wafer is ground and polished down to 450 nm.

Once the Ti:sapphire layer is thinned, it needs to be etched to create a waveguide, illustrated in figure 2, that serves as the laser cavity. The spiral waveguide, seen in figure 3, keeps the light inside the lasing medium for longer, thereby amplifying the light, than if the light had taken a straight path. Sapphire's hardness makes waveguide etching a difficult and often long process. So the researchers developed a pattern-transfer method that uses an electron-beam photoresist and a chromium mask that can withstand the lithography process.

In tabletop Ti:sapphire lasers, the pump and lasing modes only partially overlap, which limits the pumping efficiency and increases the pump-power requirements. But the on-chip waveguide achieves a near-perfect overlap between the pump and lasing modes, which increases the efficiency of the system and allows the laser threshold to be reached with a lower-power pump laser.

The laser developed by the Vučković group has a spiraling waveguide with a footprint of only 0.15 mm^2, and it can be pumped with an off-the-shelf 110 mW green laser diode. Tuning the laser across the whole 650–1100 nm range is achieved via an integrated microheater that changes the index of refraction and, hence, the resonance wavelength.

Laser technology for all

For now, the new laser operates only in continuous-wave, nonpulsed mode. It uses a basic \$37 pump laser—three orders of magnitude cheaper than full-sized pump lasers—that only weighs a

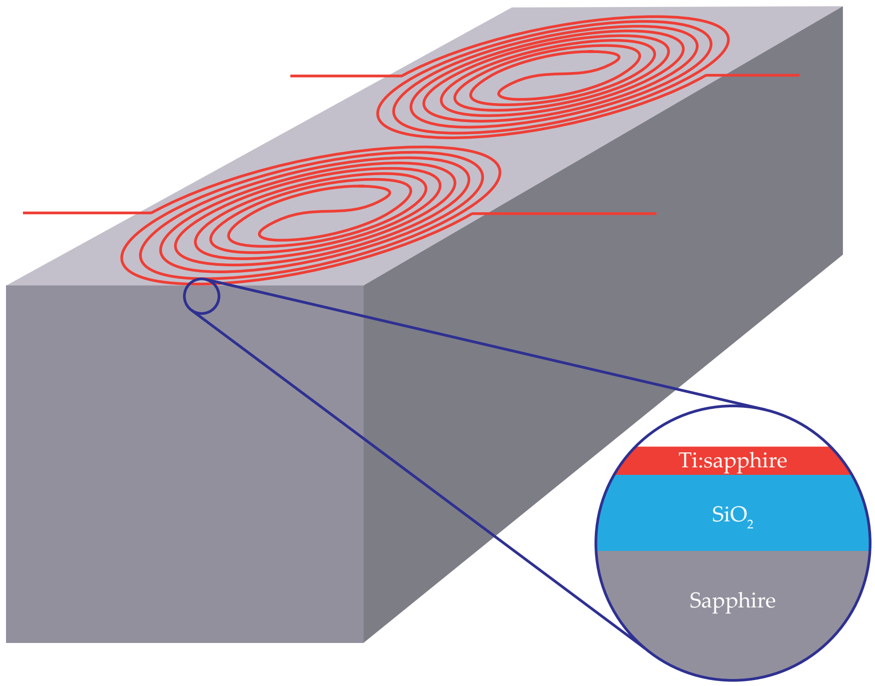

FIGURE 2. MINIATURE TITANIUM:SAPPHIRE LASERS are fabricated on a rectangular rod of sapphire. A thin layer of Ti:sapphire is connected to an intermediate layer of silica. The spiral shape of the waveguide etched from the Ti:sapphire layer increases the laser gain, and thus the output power, for a given chip size. Lasers with waveguide lengths of 3 mm and 8 mm have been constructed. (Illustration by Freddie Pagani.)

few hundred milligrams and delivers the few milliwatt output power needed. Vučković and her team have demonstrated that the laser is good enough to start using in their research experiments.

The inventors of the original Ti:sapphire laser didn't file a patent. The open technology and lack of legal complications allowed Vučković and her lab to improve on the design. Now Joshua Yang, one of Vučković's students and the first author of the paper, is starting a company to develop and distribute the tiny laser and amplifier technology.

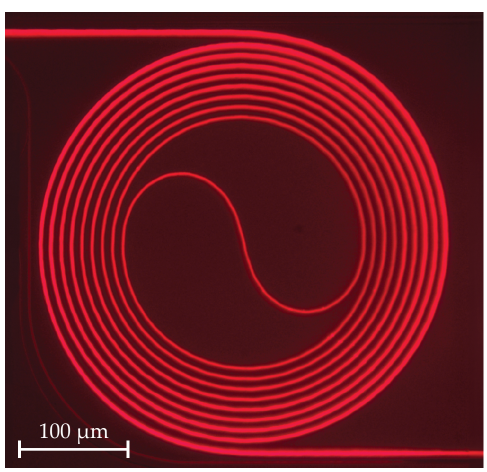

FIGURE 3. THE SPIRALING 8-MM-LONG WAVEGUIDE in a titanium:sapphire laser. The longer the waveguide, the longer the light interacts with the Ti:sapphire and can be amplified. (Adapted from ref 1.)

Meanwhile, Vučković and her group continue innovating on the design of their laser. Priorities include increasing the coupling efficiency from the current 16% and developing a pulsed version. Other plans include achieving better thermal stability based on the placement of the heater and achieving increased laser frequency stabilization.[4]

Jennifer Sieben

References

1. N. Sapra et al., *Science* **367**, 79 (2020).
2. J. Yang et al., *Nature* **630**, 853 (2024).
3. See, for example, Y. Wang et al., *Nat. Photonics* **17**, 338 (2023).
4. A. White et al., https://arxiv.org/abs/2404.03093.