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It is a quantum fractal algorithmic universe

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Quantum Sensing Tools

USC ISI researchers are trying to make quantum sensing tools, like atomic accelerometers, more compact and accurate so they can replace GPS.

Artist's impression of a GPS Block IIIA satellite in orbit. Image credit: USAF via Wikimedia, Public Domain

Fundamental physics — let alone *quantum* physics — might sound complicated to many, but it can actually be applied to solve everyday problems.

Imagine navigating to an unfamiliar place. Most people would suggest using GPS, but what if you were stuck in an underground tunnel where radio signals from satellites were not able to penetrate through? That's where quantum sensing tools come in.

USC Viterbi Information Sciences Institute researchers Jonathan Habif and Justin Brown, both from ISI's new Laboratory for Quantum-Limited Information, are working at making sensing instruments like atomic accelerometers smaller and more accurate so they can be used to navigate when GPS is down.

Tackling the size conundrum

Atoms are excellent at making accurate measurements because they are all the same. Atomic measurements made in one laboratory would be indistinguishable from those made in another laboratory, as the atoms behave in precisely the same way.

One example of how this physics concept can be applied is making a highly accurate navigation system with these atoms.

"As an atomic physicist, I work with atoms in a gas and talk to the atoms with lasers," Brown said. "As atoms have mass, they can be used to measure accelerations, helping us build atom-based sensors like atomic accelerometers."

Habif added, "The accelerometers let you know how fast and far you're moving in a given direction. They can be coupled with gyroscopes, which tell you whether you've changed directions and how far you've turned, to make a complete measurement. These navigation instruments are useful when you don't have access to GPS."

One of the challenges they're facing is how they can engineer this in a thoughtful way.

For example, they have to think very carefully about how they can miniaturize atomic accelerometers. These accelerometers have historically operated in big laboratory scale systems, where equipment is heavy and consumes a lot of power. To make the accelerometers suitable for public use, Habif and Brown are investigating how to retain their high precision in a much more compact, power-efficient and attractive medium.

Brown said, "We want to take this out in the field and make it smaller at the same time, but the techniques and supplies that we're drawing from are not very conducive to doing so just yet. I'm thinking about how to talk to the atoms in a different way so that we can get the capabilities to apply it to problems outside the laboratory."

Applications in defence and adapting to the real world

Not only do quantum sensing devices work in areas that don't have access to GPS, they can also be part of an exciting new avenue: national security applications.

"Modern conflicts are becoming increasingly electronic and less kinetic, as nations vie for information superiority. The radio signal from GPS satellites is easy to disrupt and jam because it is far away. Thus, in any modern conflict, both sides will attempt to deny each other access to these radio signals," Brown said.

"More traditional navigation instruments like inertial systems are un-jammable, as they work by adding up accelerations and rotations to measure our change in position. So they can replace GPS in times of conflict. However, all the errors made also get added up, so we are interested in using an atom-based measurement to ensure it is more accurate."

Atomic accelerometers are one example of these inertial systems. These systems are present in sensors on aircraft and ships, guiding their movement through airspaces and waters. However, existing mechanical-based sensors can wear out easily due to friction, leading to them being swapped out every year and costing a lot of money. They are also hard to build because they're small and delicate.

The US Department of Defense (DoD) is looking for upgrades in their inertial systems so that these difficulties can be overcome. The quantum approach based on atoms pursued by Brown and other groups could provide acceleration measurements with no moving parts.

"For example, if submarines want to be stealthy and quiet in defense scenarios, keeping track of what it's doing and how it's moved through inertial systems is pretty much the only game in town. I'm developing ideas on improving these systems for the DoD, so that they can be downsized and more cost-efficient," noted Brown.

Simplifying the tools

Brown maintains that quantum sensing will be important on many fronts.

"Preparing for technical surprise means preparing for *when* GPS fails – the question isn't *if* GPS fails," said Brown. "It's very easy to stop GPS from working, so inertial sensors will always be useful. But it's still vital for us to solve the size issue, because a lot of these sensors still end up at about the size of a washing machine. I could simplify the tool itself, but I still need to make a good measurement."

Achieving this fine balance between simplicity and accuracy is the researchers' main goal, and they hope that their efforts will translate to real-world prototypes someday.

Quantum Light Unlocks Nature’s Tiny Secrets

Researchers at the University of Michigan have found a way to examine tiny structures, such as bacteria and genes, with reduced damage compared to traditional light sources.

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

The new technique involves spectroscopy, the study of how matter absorbs and emits light and other forms of radiation. It takes advantage of quantum mechanics to study the structure and dynamics of molecules in ways that are not possible using conventional light sources.

“This research examined a quantum light spectroscopy technique called entangled two-photon absorption that takes advantage of entanglement to reveal the structures of molecules and how ETPA acts at ultrafast speeds to determine properties that cannot be seen with classical spectroscopy,” said study senior author Theodore Goodson, U-M professor of chemistry and of macromolecular science and engineering.

Entangled two-photon absorption allows researchers to study molecules by using two photons that are interconnected through a quantum phenomenon known as entanglement.

Photons are the smallest possible particles of electromagnetic energy and, therefore, also the smallest particles of light, allowing details about the molecule’s structure to be visible—which cannot be shown with regular light. Quantum light spectroscopy is very fast and can reveal properties that are usually hidden.

The discovery opens opportunities for non-invasive, low-intensity imaging and sensing applications with minimal photodamage to delicate biological samples like proteins, DNA, and living cells.

“Measurements with entangled photons may enable sensing biological signatures with high selectivity and at very low light levels to protect against photodamage,” said lead author Oleg Varnavski, a research lab specialist in the U-M Department of Chemistry.

The research, published in the Proceedings of the National Academy of Sciences, used an organic molecule called zinc tetraphenyl porphyrin to study the phenomenon of two-photon absorption—where a molecule simultaneously absorbs two particles of light instead of one.

Researchers found that using pairs of photons that were quantumly entangled, the ZnTPP molecule exhibited absorption in the red spectrum. With two untangled photons, the ZnTPP molecules showed absorption in a blue spectrum.

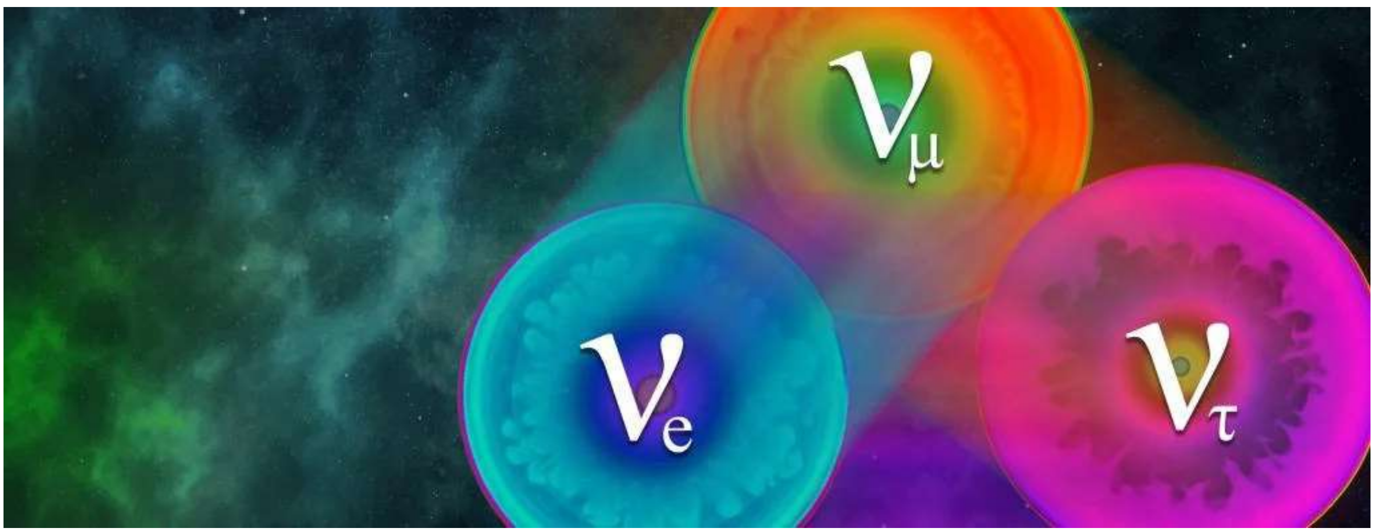
A laser produced pairs of entangled photons through a process called spontaneous parametric down-conversion. These photons were then focused onto a cuvette containing the ZnTPP solution. The transmission was measured using a highly sensitive single-photon detector.

This work paves the way for the advancement of quantum light-based spectroscopy and microscopy, potentially leading to much higher efficiency of ETPA sensors and low-intensity detection schemes. The ability to access unique molecular states with entangled photons could improve the sensing of biological signatures with significant selectivity and sensitivity even at minimum light levels to prevent photodamage.

“This provides the opportunity to study states of molecules with nonclassical light that have fundamentally different properties than are accessible with classical light,” Varnavski said.

Untangling The Entangled: Quantum Study Shines Fresh Light On How Neutrinos Fuel Supernovae

Researchers used quantum simulations to obtain new insights into the nature of neutrinos — the mysterious subatomic particles that abound throughout the universe — and their role in the deaths of massive stars.



Researchers used quantum simulations made possible by ORNL's Quantum Computing User Project to model the flavor oscillations of neutrinos in a supernova. Neutrinos come in three "flavors," or types, that each correspond to a partner particle: an electron (e), a muon (µ), or a tau (†). Credit: ORNL, U.S. Dept. of Energy

The study relied on support from the Quantum Computing User Program, or QCUP, and the Quantum Science Center, a national Quantum Information Science Research Center, at the Department of Energy's Oak Ridge National Laboratory.

"This understanding was something new that hasn't come out of classical computing systems," said Martin Savage, the study's senior author and a professor of physics at the University of Washington. "We recognized for the first time we could study how entanglement between multiple neutrinos is induced over time, and these results are within the error bars of what we'd expect from a classical computer. It's a step in the direction of better, more accurate and more scalable quantum simulations."

Neutrinos result from nuclear reactions — from the huge reactions that cause the sun to shine, to the tiny reactions that enable radioactive tracers for medical tests. These extremely light particles appear everywhere, carry no electric charge and seldom interact with other matter.

But during the collapse and explosion of a star — a process better known as a supernova — neutrinos exchange energy and momentum with not just each other but with everything around them.

"At this point, the neutrinos go from passive particles — almost bystanders — to major elements that help drive the collapse," Savage said. "Supernovae are interesting for a variety of reasons, including as sites that produce heavy elements such as gold and iron. If we can better understand neutrinos and their role in the star's collapse, then we can better determine and predict the rate of events such as a supernova."

Scientists seldom observe a supernova close-up, but researchers have used classical supercomputers such as ORNL's Summit to model aspects of the process. Those tools alone wouldn't be enough to capture the quantum nature of neutrinos.

"These neutrinos are entangled, which means they're interacting not just with their surroundings and not just with other neutrinos but with themselves," Savage said. "It's extremely difficult to simulate this kind of system, because entanglement's an intrinsically quantum-mechanical property beyond what we can capture and approximate in classical computing. That's why we need a quantum computer that uses calculations based on quantum physics to model what's happening."

Savage and his co-author Marc Illa of the University of Washington's InQubator for Quantum Simulation obtained an allocation of time on Quantinuum's H1-1 quantum computer via QCUP, part of the Oak Ridge Leadership Computing Facility, which awards time on privately owned quantum processors around the country to support research projects. The Quantinuum computer uses trapped ions as qubits, one of several quantum computing approaches.

Classical computers store information in bits equal to either 0 or 1. In other words, a classical bit, like a light switch, exists in one of two states: on or off.

Quantum computers store information in qubits, the quantum equivalent of bits. Qubits, unlike classical bits, can exist in more than one state simultaneously via quantum superposition – more like a dial with a wider range of more detailed settings than an on/off switch. That difference enables qubits to carry more information than classical bits.

Scientists hope to use this increased capacity to fuel a quantum computing revolution built on a new generation of devices.

That capacity allowed Savage and the research team to simulate an approximation of the quantum-mechanical interactions between a supernova's neutrinos. An actual supernova would involve a minimum of a septendecillion, or 10^{54}, neutrinos. Savage and Illa began their simulation using a simpler model with a system of 12 neutrinos.

Each neutrino "flavor," or type, found in nature corresponds to a "partner" particle: an electron, muon or tau. The model used in the study focused on just two flavors.

Quantum circuits – the quantum equivalent of traditional digital circuits – allowed the team to model the complicated connections and interactions between the particles so that each neutrino could interact with each of the others, not just its nearest neighbours.

The results offered a realistic approximation of how neutrinos become entangled at the quantum level, so that changing the properties of one also changes the properties of another. During a supernova, neutrinos can change flavor from an electron flavor to a muon flavor or to a tau flavor as the neutrinos begin to interact with each other and their surroundings. The detail provided by the simulations enabled the team to measure the evolution from one flavor to another over time of various entangled neutrinos.

Why track the flavor conversion? Because the mu and tau flavors of neutrinos interact differently with matter than their electron-flavored brethren. These interactions can impact the amounts and types of heavier elements produced in the supernova explosion.

"These circuits turned out to approximate the neutrinos' behavior very well," Savage said. "We discovered we could use these simulations to measure neutrino entanglement in a statistically significant way and that we could identify a significant scaling in size as the number of neutrinos increased. This was the first time this kind of study had been done."

The primary hurdle for useful quantum simulations has been the relatively high error rate caused by noise that degrades qubit quality. The problem's so common the current generation of quantum computers has become known as noisy intermediate-scale quantum, or NISQ. Various programming methods can help reduce these errors, but Savage and Illa didn't need those methods to conduct their study thanks to the high quality of the Quantinuum computer's qubits and gates. The computer's 12-qubit circuits proved to be sufficient for almost 200 of the 2-qubit gates.

"We found the systematic errors on the quantum hardware were less than the statistical errors," Savage said. "We still have a long way to go to predict the behavior of large neutrino systems with precision, and we don't know whether the current generation of NISQ devices can take us there. But this technique should be portable to other types of quantum computers, and the results help us set protocols that can be used to simulate larger systems of neutrinos."

Next steps include simulating a system of as many as 50 neutrinos. Savage hopes to model such systems in a variety of environments.

“We want to understand the implications of different thermal states, of states in and out of equilibrium,” he said. “We’re excited to see what we can explore.”

Support for this research came from the DOE Office of Science’s Advanced Scientific Computing Research program, the DOE Quantum Science Center and the DOE Nuclear Physics InQubator for Quantum Simulation. The OLCF is a DOE Office of Science user facility at ORNL.

Is A Gamma-Ray Laser Possible?

Federal funding will allow Rochester scientists and their European collaborators to study the feasibility of coherent light sources beyond X-rays.

GAMMA-RAY GOALS: The experimental hall at ELI Beamlines where the experiments led by University of Rochester scientist Antonino Di Piazza will be performed. If successful, the research could lead to the creation of a gamma-ray free electron laser, a major goal in the scientific community. Image credit: ELI Beamlines

Since the laser was invented in the 1960s, scientists have been working to increase lasers' peak power and to design machines producing coherent light at progressively shorter wavelengths that can improve image resolution and enable probing of quantum nuclear states.

Progress has been made with regard to peak power, most notably with the invention of chirped pulse amplification by University of Rochester researchers in the 1980s, a breakthrough that garnered the Nobel Prize in Physics in 2018. However, developing lasers that produce very-high-energy light, such as gamma rays, has remained elusive. That's in part because "coherent" light waves are in sync with each other, creating a stronger effect in combination. This effect is harder to achieve at higher-photon energies. And while lasers can now produce coherent light in the visible, ultraviolet, and x-ray ranges of the electromagnetic spectrum, doing so beyond the x-ray range—which is where gamma rays exist—remains a challenge.

To overcome this obstacle, Rochester researchers secured National Science Foundation (NSF) funding in collaboration with colleagues from ELI Beamlines in the Czech Republic to investigate the coherence properties of the radiation emitted when dense bunches of electrons collide with a strong laser field. In doing so, the researchers aim to understand how to produce coherent gamma rays and use these new radiation sources for research and applications to create antimatter, study nuclear processes, and image dense objects or materials, such as scanning shipping containers.

"The ability to make coherent gamma rays would be a scientific revolution in creating new kinds of light sources, similar to how the discovery and development of visible light and x-ray sources changed our fundamental understanding of the atomic world," says Antonino Di Piazza, a professor of physics at the University of Rochester and a distinguished scientist at the University's Laboratory for Laser Energetics, who is the lead investigator on the NSF grant.

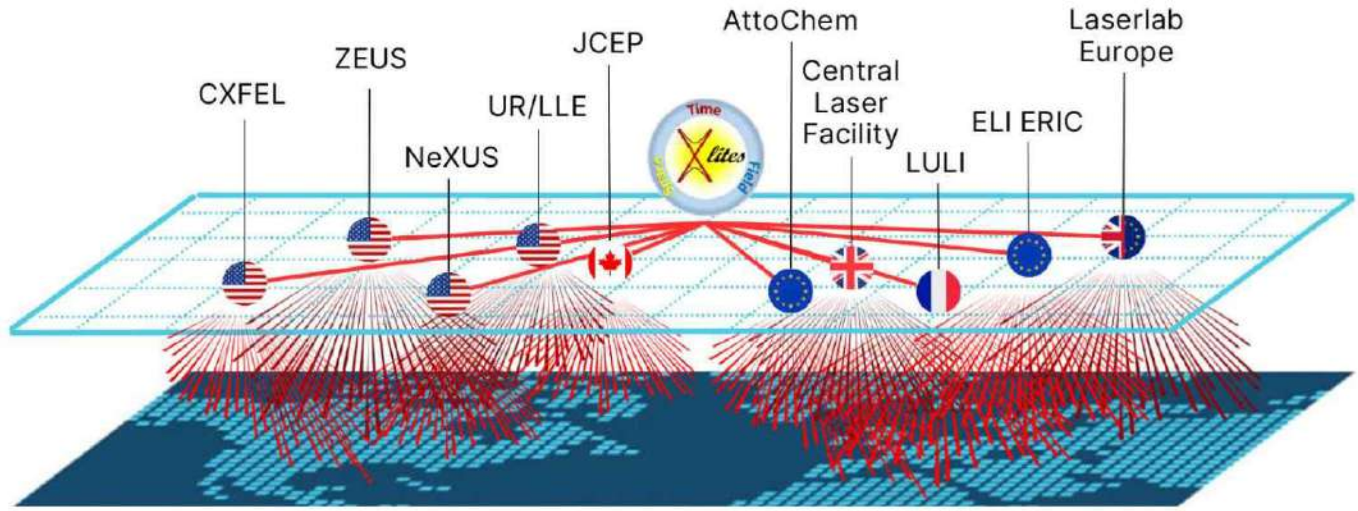
US–Europe connections facilitate laser science advancements

The project combines the theoretical expertise of Rochester scientists with the theoretical and experimental capabilities of ELI Beamlines in the Czech Republic, strengthening ties between the US and Europe in the field of high-intensity lasers.

The scientists will use complex theories and high-tech experiments to study how fast-moving electrons interact with the laser to emit high-energy light. They'll start by looking at simpler cases, such as how one or two electrons emit light, before moving on to more complicated scenarios with many electrons, to produce coherent gamma rays. Such a result builds on the work of scientists who have created coherent x-rays, including the teams at SLAC National Accelerator Laboratory, European XFEL, and SACLA.

"We are not the first scientists who have tried creating gamma rays in this way," says Di Piazza. "But we are doing so using a fully quantum theory—quantum electrodynamics—which is an advanced approach to addressing this problem."

If successful, this project could lead to the creation of a gamma-ray free electron laser, a major goal in the scientific community, according to Di Piazza. "Of course," he says, "step one is to show that the science is possible before building such a device."



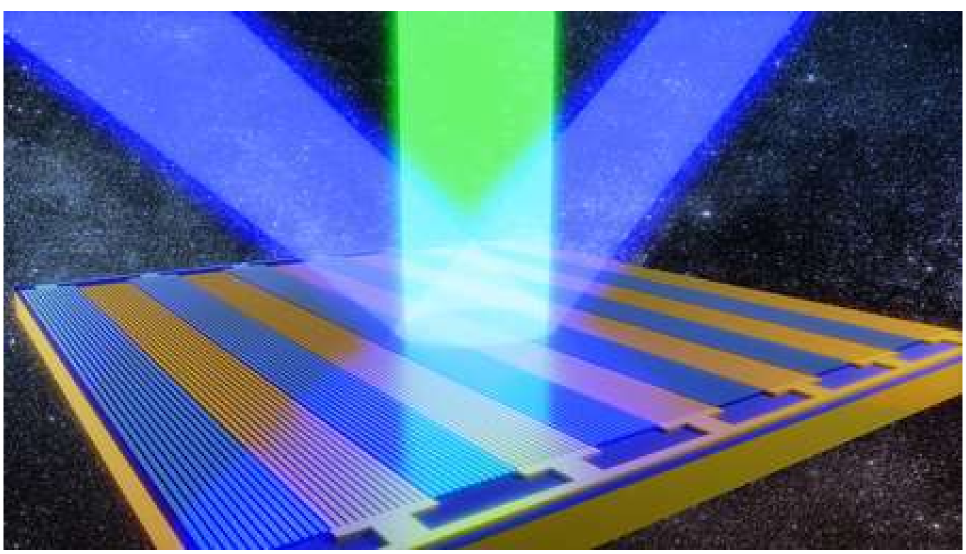
NET(WORK) EFFECT: The University of Rochester's Laboratory for Laser Energetics is part of the NSF X-Lites, a "network of networks" studying extreme light in intensity, time, and space. Image credit: NSF X-Lites

This work will also contribute to advancing the science case for a potential future NSF OPAL high-power laser user facility at the University of Rochester, another NSF-funded project on which Di Piazza is a co-principal investigator, and which has the potential to be a unique open-access resource for the global scientific community. NSF OPAL is part of NSF X-lites, an international network of networks studying extreme light in intensity, time, and space formed to address the grand challenge questions defined at the frontiers of laser-matter coherent interactions at the shortest distances, highest intensities, and fastest times.

Nanoscale Device Simultaneously Steers And Shifts The Frequency Of Optical Light, Pointing The Way To Future Wireless Communication Channels

It is a scene many of us are familiar with: You're working on your laptop at the local coffee shop with maybe a half dozen other laptop users—each of you is trying to load websites or stream high-definition videos, and all are craving more bandwidth.

Now imagine that each of you had a dedicated wireless channel for communication that was hundreds of times faster than the Wi-Fi we use today, with hundreds of times more bandwidth. That dream may not be far off thanks to the development of metasurfaces—tiny engineered sheets that can reflect and otherwise direct light in desired ways.



An incident laser beam (green) hits Caltech's new space-time metasurface and gets modulated by tunable, nanostructured antennas, creating steerable beams of light at different frequencies (blue) that could be used as optical channels for transmitting data on Earth or in space. Image Credit: Caltech

In a paper published in the journal *Nature Nanotechnology*, a team of Caltech engineers reports building such a metasurface patterned with miniscule tunable antennas capable of reflecting an incoming beam of optical light to create many sidebands, or channels, of different optical frequencies.

"With these metasurfaces, we've been able to show that one beam of light comes in, and multiple beams of light go out, each with different optical frequencies and going in different directions," says Harry Atwater, the Otis Booth Leadership Chair of the Division of Engineering and Applied Science, the Howard Hughes Professor of Applied Physics and Materials Science, and senior author on the new paper. "It's acting like an entire array of communication channels. And we've found a way to do this for free-space signals rather than signals carried on an optical fiber."

The work points to a promising route for the development of not only a new type of wireless communication channel but also potentially new range-finding technologies and even a novel way to relay larger amounts of data to and from space.

Going beyond conventional optical elements

Co-lead author on the new paper Prachi Thureja, a graduate student in Atwater's group, says to understand their work, first consider the word "metasurface." The root, "meta," comes from a Greek prefix meaning "beyond." Metasurfaces are designed to go *beyond* what we can do with conventional bulky optical elements, such as camera or microscope lenses. The multilayer transistor-like devices are engineered with a carefully selected pattern of nanoscale antennas that can reflect, scatter, or otherwise control light. These flat devices can focus light, in the style of a lens, or reflect it, like a mirror, by strategically designing an array of nanoscale elements that modify the way that light responds.

Much previous work with metasurfaces has focused on creating passive devices that have a single light-directing functionality that is fixed in time. In contrast, Atwater's group focuses on what are known as active metasurfaces. "Now we can apply an external stimulus, such as an array of different voltages, to these devices and tune between different passive functionalities," says Jared Sisler, also a graduate student in Atwater's lab and co-lead author on the paper.

In the latest work, the team describes what they call a space-time metasurface that can reflect light in specific directions and also at particular frequencies (a function of time, since frequency is defined as the number of waves that pass a point per second). This metasurface device, the core of which is just 120 microns wide and 120 microns long, operates in reflection mode at optical frequencies typically used for telecommunications, specifically at 1,530 nanometers. This is thousands of times higher than radio frequencies, which means there is much more available bandwidth.

At radio frequencies, electronics can easily steer a beam of light in different directions. This is routinely accomplished by the radar navigation devices used on airplanes. But there are currently no electronic devices that can do this at the much higher optical frequencies. Therefore, the researchers had to try something different, which was to change the properties of the antennas themselves.

Sisler and Thureja created their meta-surface to consist of gold antennas, with an underlying electrically tunable semiconductor layer of indium tin oxide. By applying a known voltage profile across the device, they can locally modulate the density of electrons in the semiconductor layer below each antenna, changing its refractive index (the material's light-bending ability). "By having the spatial configuration of different voltages across the device, we can then redirect the reflected light at specified angles in real time without the need to swap out any bulky components," Thureja says.

"We have an incident laser hitting our metasurface at a certain frequency, and we modulate the antennas in time with a high-frequency voltage signal. This generates multiple new frequencies, or sidebands, that are carried by the incident laser light and can be used as high-data-rate channels for sending information. On top of this, we still have spatial control, meaning we can choose where each channel goes in space," explains Sisler. "We are generating frequencies *and* steering them in space. That's the space-time component of this metasurface."

Looking toward the future

Beyond demonstrating that such a metasurface is capable of splitting and redirecting light at optical frequencies in free space (rather than in optical fibers), the team says the work points to several possible applications. These metasurfaces could be useful in LiDAR applications, the light equivalent of radar, where light is used to capture the depth information from a three-dimensional scene. The ultimate dream is to develop a "universal metasurface" that would create multiple optical channels, each carrying information in different directions in free space.

"If optical metasurfaces become a realizable technology that proliferates, a decade from now you'll be able to sit in a Starbucks with a bunch of other people on their laptops and instead of each person getting a radio frequency Wi-Fi signal, they will get their own high-fidelity light beam signal," says Atwater, who is also the director of the Liquid Sunlight Alliance at Caltech. "One metasurface will be able to beam a different frequency to each person."

The group is collaborating with the Optical Communications Laboratory at JPL, which is working on using optical frequencies rather than radio frequency waves for communicating with space missions because this would enable the ability to send much more data at higher frequencies. "These devices would be perfect for what they're doing," says Sisler.

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