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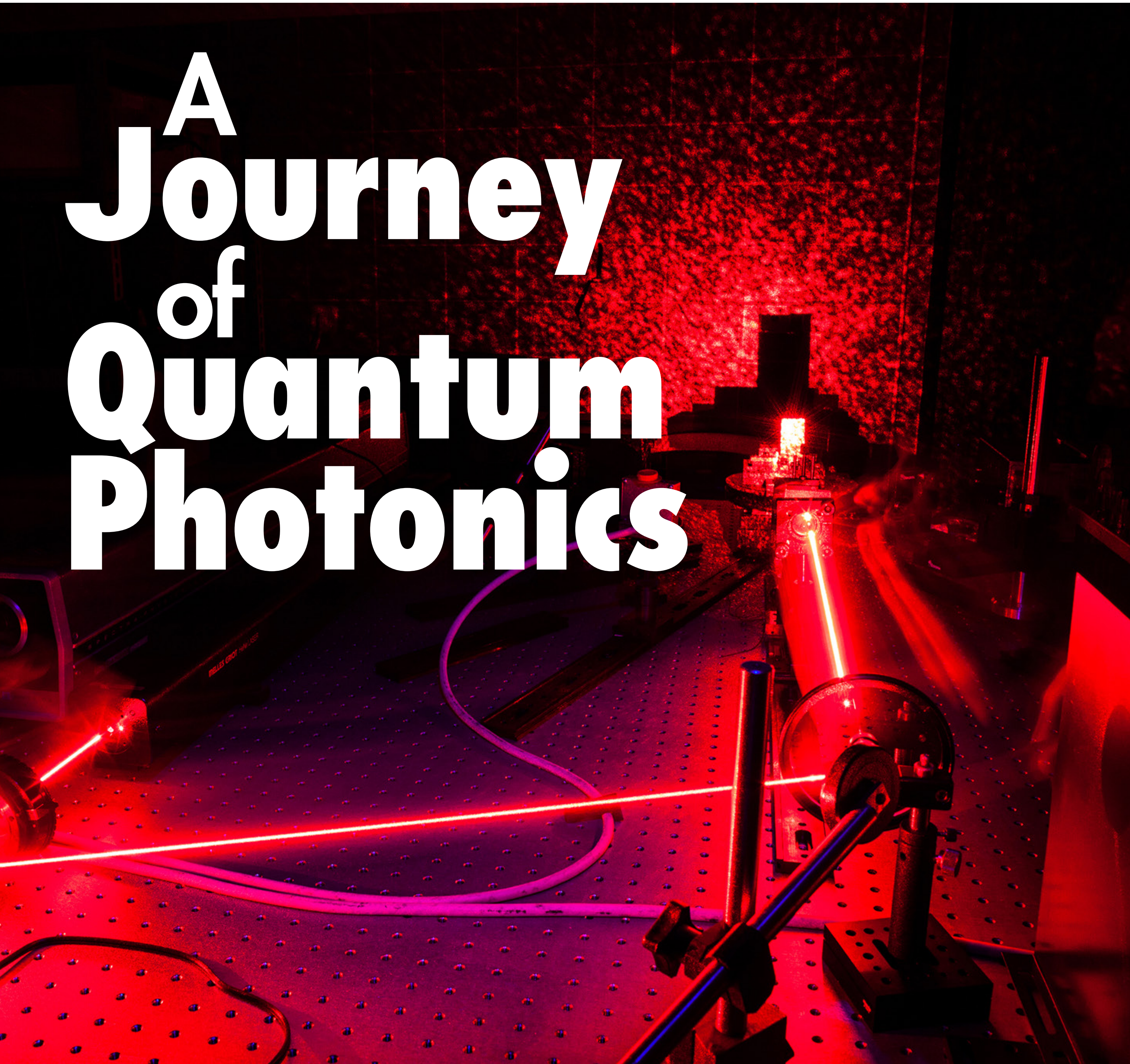
A Journey of Quantum Photonics



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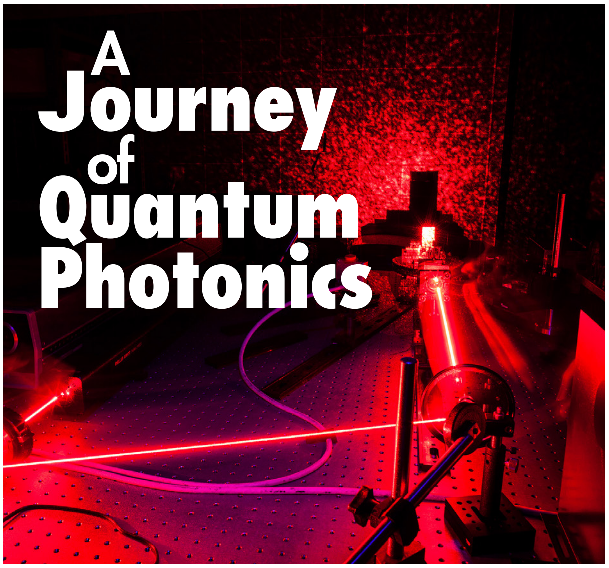
A Journey of Quantum Photonics



Laser Focus World invites you to join us on a quantum journey as we share the work of researchers around the globe pushing quantum mechanics closer to real-world applications in quantum computers, quantum networks, and secure encrypted communications.

Peter Fretty
Editor-in-chief
Laser Focus World

2022 was a turning point for quantum work, with the Nobel Prize in Physics going to Alain Aspect, John F. Clauser, and Anton Zeilinger for their experiments with entangled photons, establishing the violation of Bell inequalities, and pioneering quantum information science.

Nearly all the laser, optics, and photonics research we cover has links or ties to quantum work or a future quantum application—and this is just the beginning. Whether you're new to the quantum realm or actively helping to push its boundaries, we've got something for you here.

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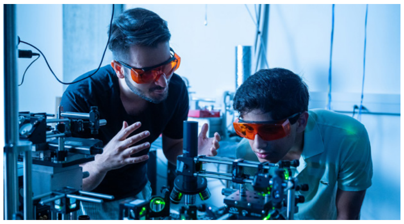

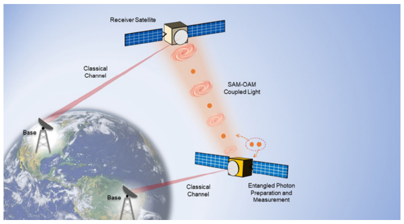

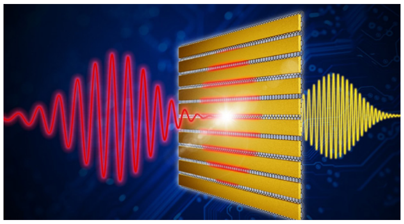

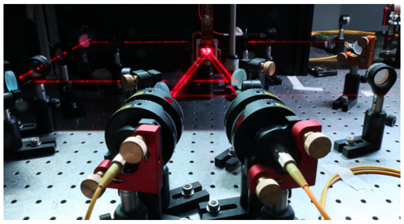

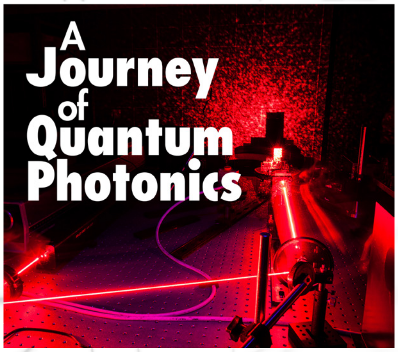

FIGURE 1. Kamyar Parto (left) works in the Moody Quantum Photonics Lab with Arjun Choudhri, a high school student he mentored last summer.

CHAPTER 1:

Quantum photonics: On-chip generation of single photons

SALLY COLE JOHNSON, Senior Technical Editor, Laser Focus World

The Moody Quantum Photonics Lab at University of California – Santa Barbara (UCSB) efficiently collects and funnels photons from quantum emitters by embedding them into a photonic waveguide for on-chip routing.

In a significant quantum advance, University of California – Santa Barbara (UCSB) researchers recently created a method to produce a fast and steady stream of single photons—essential for enabling photonics-based quantum technologies.

Collecting photons efficiently is difficult because quantum emitters can emit single photons in nearly any direction, so they need to be placed into an intermediary medium (think funnel) to be collected and directed onto a specific path of travel.

To do this, the researchers are using an on-chip optical cavity (ring resonator) as their intermediary medium, which collects most of the light from the single photon sources and funnels it to an on-chip waveguide very efficiently.

Putting these single photons into many different waveguides—a thousand single photons on each waveguide—means they can choreograph how the photons travel along the waveguides on chip, which, in turn, enables quantum computation.

Shrinking optical systems onto photonic chips

The quantum photonics field has been developing along with other competing platforms for years, "but maybe with less hype," says Kamyar Parto, a Ph.D. student working with Galan Moody, a quantum photonics expert and assistant professor of electrical and computer engineering at UCSB.

"In the past few years, researchers have demonstrated bulk tabletop optical systems capable of achieving a quantum advantage for specific tasks, demonstrating the capabilities of photonics for quantum computing," says Moody. "But ultimately, these optical systems need to be shrunk down onto photonic chips that can be networked together to become scalable and manufacturable."

Quantum computing platforms rely on defining a qubit, doing operations on qubits, and then measuring their quantum states. For a quantum photonics approach, quantum information is encoded onto the properties of single photons, such as the orientation of their electric field, frequency, or their path of travel.

"For quantum photonic computing, it's then a matter of generating streams of high-quality single photons with high efficiency, making different streams of photons interact with each other to carry out computations, and then detecting the photons," says Moody.

This can all be achieved via tabletop setups and routing photons around using mirrors and other optical components (**see Fig. 1**), but Parto points out it's possible to run out of room on your optical table quickly. "Integrated quantum photonics allows you to bring almost everything you can do on an optical table to a chip, where everything is condensed and stable," he says. "For instance, you can route the light to specific locations on the chip using waveguides, where other components then act to manipulate the properties of the photons or detect them."

Generating high-quality photons via 2D materials

Since single-photon sources in two-dimensional (2D) materials were discovered about eight years ago, the quantum community has made progress characterizing, controlling, and engineering these sources.

While most materials we're familiar with can grow their crystal in all 3D of space, 2D materials like graphene and tungsten diselenide only have 2D atomic bonds, which makes them extremely thin. It's the inherent thinness and confinement in one direction, Parto says, that can make these materials unique in their electro-optical properties.

"The defects in these materials are atomic point defects," he explains. "They can be as simple as just one missing atom from the crystal and, because of this, they go beyond the diffraction limit and can't be seen with a normal microscope."

But the researchers can identify their position by scanning a tiny laser spot (<300 nm) over the materials to look for the optical signatures of the defect (**see Fig. 2**).

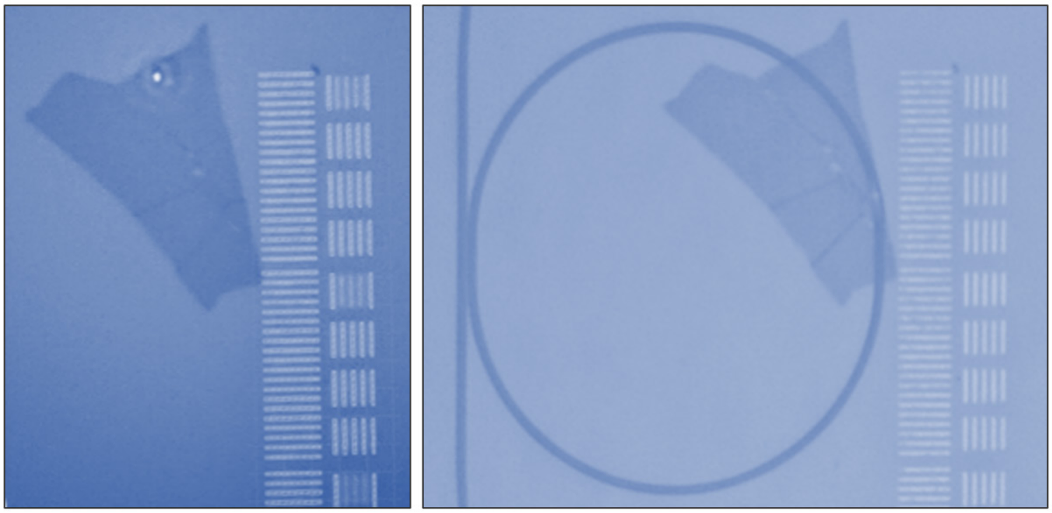

FIGURE 2. Crafting 2D defects: On the left, you can see a 2D material flake. On the right, you can see the ring resonator passing through the same laser spots, and now the defect is sitting precisely under the optical cavity. (Image credit: Moody Lab/UCSB)

"2D materials have remarkable properties, such as the ability to operate at room temperature," says Parto. "These materials can also be integrated with nearly any other material system, which opens up lots of opportunities—not only in quantum information and communications, but also sensing, optoelectronics, biology, and chemistry."

For these materials to be useful for quantum information, it's important to collect as many emitted photons as possible. A major hurdle for quantum photonics, however, is generating high-quality photons in the first place, and collecting and guiding these photons on a chip efficiently. "This is the focus of our project using a relatively new material system based on 2D crystals," says Parto, who is working toward his Ph.D. on engineering defects within 2D semiconductor materials.

There are many ways to generate single photons, but the Moody Lab researchers are crafting defects within certain 2D semiconductor materials that are only one atom thick (**see Fig. 3**). To create a defect, they essentially remove a tiny amount of material.

When you shine laser light onto one of these defects, the material responds "by emitting single photons," says Parto. "The defect acts as a rate-limiting state, which allows it to behave like a 'factory' for pushing out single photons, one at a time."

One big advantage of 2D materials is they lend themselves to having defects engineered into them. Further, Parto says "these materials are so thin, you can pick them up and put them on any other material without being constrained by the lattice geometry of a 3D crystal material. This makes the 2D material very easy to integrate."

Alignment

One of the coolest aspects of this work for Parto was aligning the position of the quantum light source, which is an atomic defect within the material, to the center of the 600-nm-wide

FIGURE 3. The Moody Quantum Photonics Lab, where the magic happens. (Photo credit: Moody Lab/UCSB)

waveguide with sub-100-nm precision.

"There's almost no room for error," he says. "For the alignment, we used a relatively inexpensive and custom-made optical microscope to identify the position of the quantum defects. But at that scale, the optical image distortions usually make any atomic-scale alignment impossible. With a few little tricks, we corrected most of the image distortions and achieved the accuracy we needed. Everyone was surprised we could still do so much with relatively simple and old technology."

Ultimate goal

The ultimate goal for single-photon sources "is a device where you can push a button and a single photon would shine into your waveguide with perfect efficiency," says Parto. "All the metrics we care about revolve around this concept. For instance, you want to ensure that every time you push a button you get a single photon into the mode—no misses allowed. You want all photons to have the same phase and frequency, to be indistinguishable from each other."

The quantum photonics community is advancing fast on all of these fronts and, "the next step for us is to realize another requirement: to make tens to hundreds or thousands of these devices on a chip," he adds.

At this scale, it becomes impractical to trigger these single photons using lasers, as Moody's lab is doing now. "To make things scalable, we need to create single-photon light-emitting diodes (LEDs) we can trigger with electrical signals," says Parto. "This is a special type of LED because light from LEDs generally shine everywhere, but we want a single-photon LED that shines solely into the unique mode of a waveguide. Our previous work is a stepping stone toward this, and now we hope to show that creating such a complicated electro-optical device is possible by leveraging the unique properties of 2D materials."

FURTHER READING

K. Parto et al., *Nano Lett.*, 22, 23, 9748-9756 (2022); doi:10.1021/acs.nanolett.2c03151.

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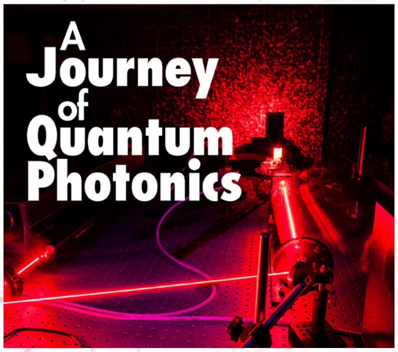

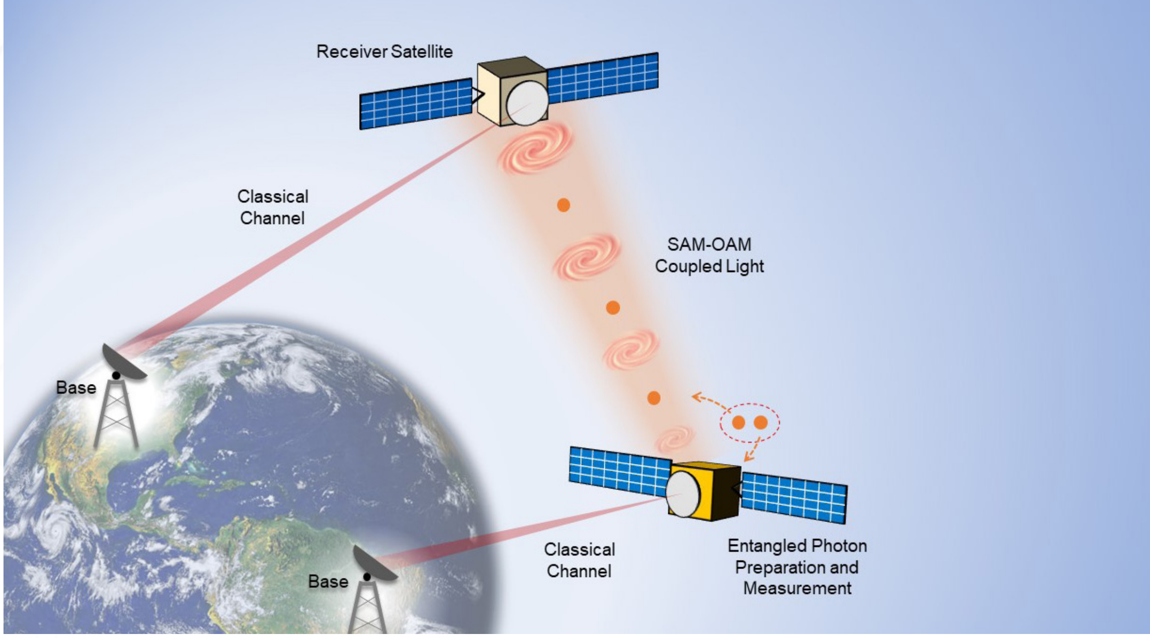

FIGURE 1. One potential application of the hyperdimensional microlaser chip is as a satellite-to-satellite high-dimensional quantum link.

CHAPTER 2:

Quantum communications get added dimensions, thanks to microlaser chip

SALLY COLE JOHNSON, Senior Technical Editor, Laser Focus World

> A hyperdimensional microlaser chip that communicates via qudits doubles the quantum information space of previous on-chip lasers—improving security and robustness far beyond existing quantum communications hardware.

A team of researchers, led by Professor Liang Feng's Lab at the University of Pennsylvania (Philadelphia, PA), designed and built a hyperdimensional microlaser to emit photons possessing any states within a four-level quantum system consisting of spin angular momentum and orbital angular momentum with very high fidelity.

This work is a huge leap forward because the team's microlaser chip can be used as a source in free-space quantum key distribution (QKD) and coherent classical communications, particularly for satellite-to-Earth communications or tower-to-tower communications (**see video**).

Classical information theory based on binary digits (bits) forms the backbone of modern information processing and communication systems. "Inspired by the achievement in classical information, quantum information processing today is mainly based on quantum bits (qubits), which can process a value of 0 or 1 at the same time—known as ‘superposition’ in quantum mechanics,” says Feng.

As the ability to control different two-level quantum systems developed, several quantum protocols and algorithms were proposed and deployed, which enabled secure communications and exponential computation speedups.

Looking beyond qubits to qudits

But qubits may not be the ideal choice to encode quantum information, because quantum system qudits—a quantum bit in a state of superposition greater than two levels—offer advantages for information processing.

“In quantum communications with photons, for example, systems using qubits can only transmit 1 bit/photon with a perfect quantum channel,” explains Feng. “But with N-level qudits, Log2 (N) bits/photon of information can be transmitted. It’s been proven that communication systems built on qudits are more robust and can pave the way for a futuristic mature quantum communications network.”

Multiple attempts are already being made to control high-dimensional quantum systems. “In a photonic system, large-scale on-chip photonic processors are being developed for both high-dimensional classical and quantum integrated information processing, where the information is mainly encoded in multiple ‘paths,’ or which waveguide the photon is in,” says Haoqi Zhao, a Ph.D. student working with Feng. “This encoding method is appropriate for on-chip information processing, but it could be difficult to use for long-distance free-space communications.”

But the angular momentums of photons, including their spin angular momentum, looks promising for long-distance high-dimensional communications—especially for satellite-to-Earth communications and tower-to-tower communications (**see Fig. 1**).

To date, “several experiments have tested high-dimensional information transmission with angular momentums of light, but all of them used multiple bulky free-space optical components, including waveplates, polarizers, phase plates, and spatial light modulators to encode information, which limits the development of angular momentum-based communication systems to a large extent,” says Zhao.

Emission and manipulation of the high-dimensional angular momentum states of photons must be developed to move this

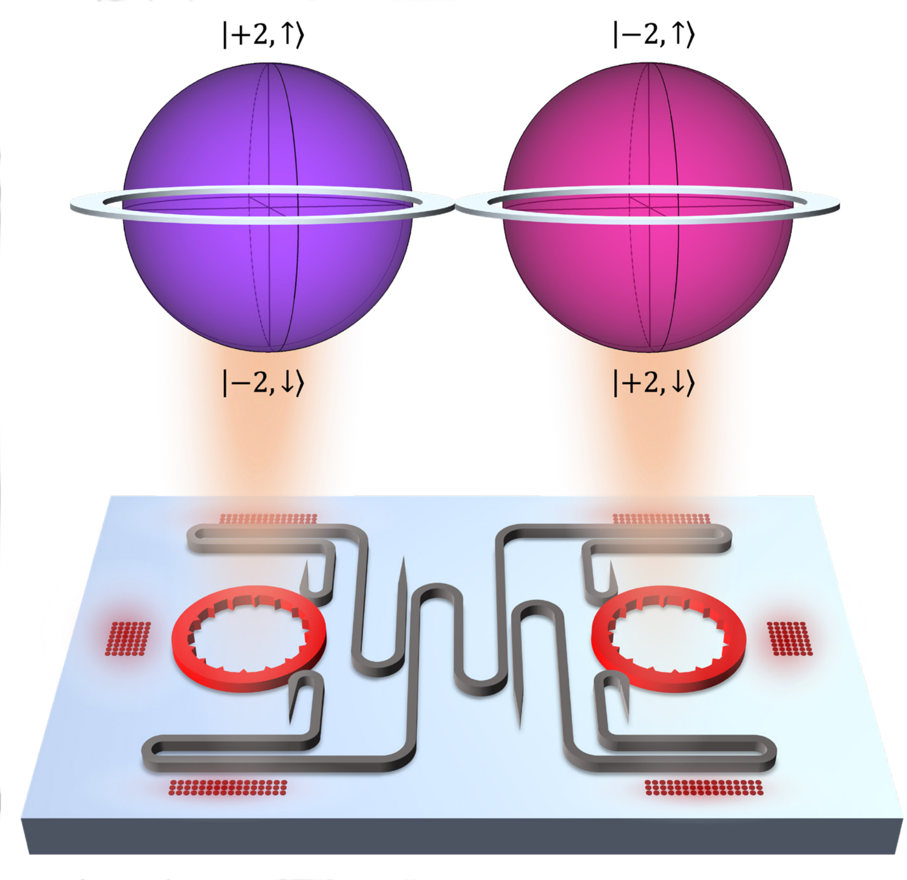

FIGURE 2. Illustration of the team’s hyperdimensional microlaser chip, which generates qudits or photons with four simultaneous levels of information. (Image credit: Haoqi Zhao)

field forward. “Our previous works showed integrated lasers emitting photons can carry well-defined angular momentum,” Zhao adds. “So we set out to develop a lasing system to emit photons whose state can be arbitrarily maneuvered within a 4-dimensional (4D) angular momentum space.”

Hyperdimensional microlaser chip design

The team’s microlaser chip consists of two same-sized micro-ring resonators on a III-V semiconductor platform (**see Fig. 2**). Each ring resonator can host two optical modes: a clockwise propagating mode and a counterclockwise propagating mode.

“These four modes can be transferred to free-space modes carrying different spin angular momentum and orbital angular momentum with designed scatters—spanning a 4D system,” points out Zhao.

This four-level system can be represented by three coupled spheres, with six free

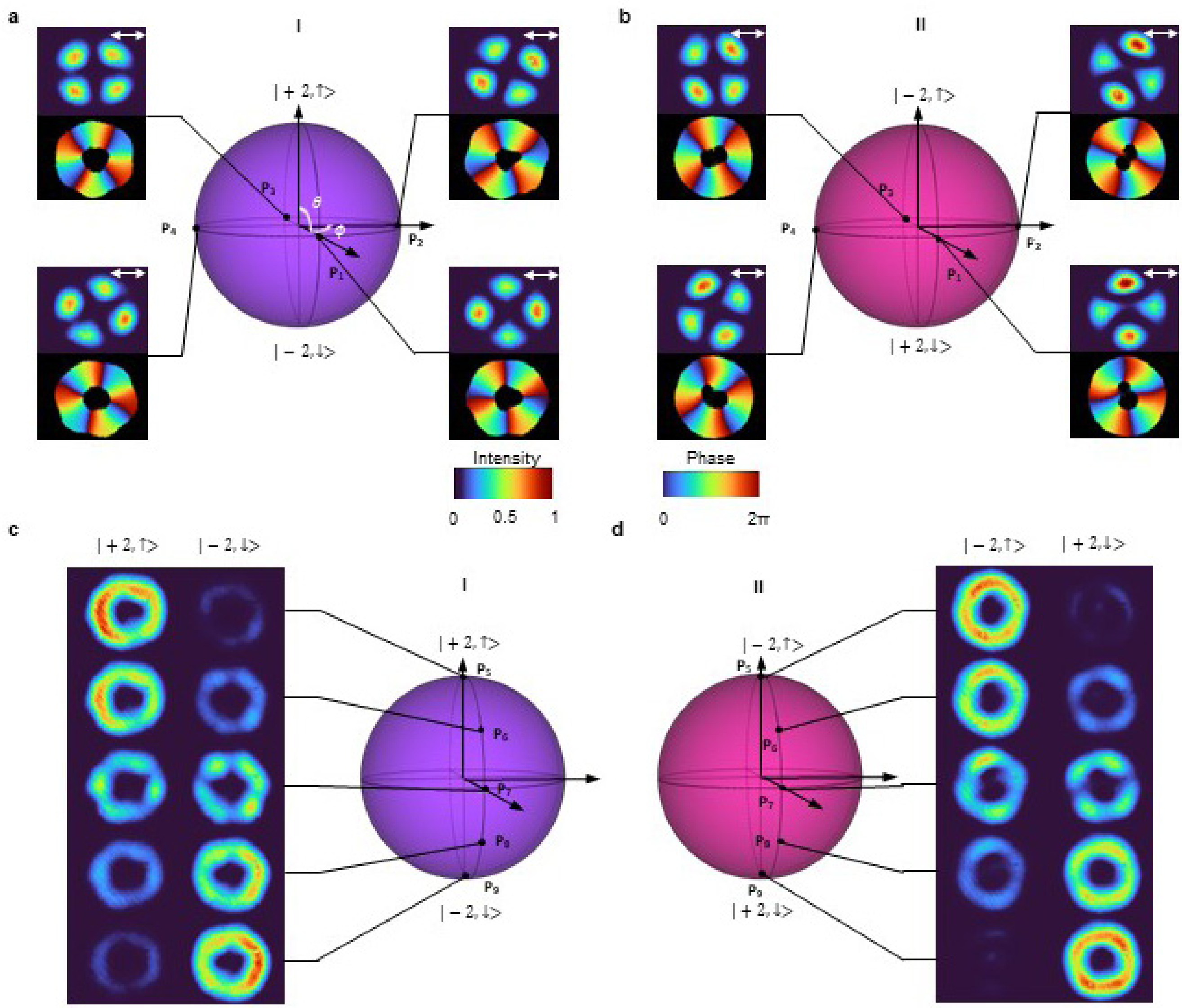

FIGURE 3. Arbitrary emission control on distinguished Bloch spheres (a geometrical representation of the state space of a two-level quantum mechanical system). Image credit: Zhifeng Zhang

parameters to control **(see Fig. 3)**. Each sphere possesses two free parameters akin to longitude and latitude on Earth.

"Our goal is to control these six parameters," explains Zhao. "So we fabricated optical waveguides to guide the light from one ring resonator to the other. When light is guided inside the waveguide, power can be either amplified or attenuated, controlled by the external optical pump. The temperature of the waveguide can also be changed, which can change the phase delay of the light."

The team demonstrated their method's ability to control all six parameters and emit any states within this 4D space. This means the microlaser can be used as a 4D qudits distribution source, as well as an optical source in coherent classical communications.

One of the biggest challenges for the team while developing the microlaser was using a linear model to describe the system—a microlaser is a nonlinear system and ultimately needs a nonlinear model to describe it. "While the linear model can help us design the microlaser system, it can't predict all of its behaviors," says Zhao. "Surprisingly, our microlaser successfully emits all the states within the 4D angular momentum space with high fidelity—outperforming the linear model."

Before the team's work, nearly all methods to generate optical states within an angular momentum space required use of extremely bulky tabletop optical systems that are complex and need optical alignment.

Now, any states within a 4D angular momentum space can be easily generated by controlling the microlaser chip's optical pump.

"Its scalability and compactness make it easy to deploy on communication satellites or towers, and it provides a possible solution in satellite-to-Earth communications and tower-to-tower communications—paving the way toward next-generation high-capacity, noise-resilient communications technologies," says Zhao.

Microlaser for quantum communications

The goal of quantum communications is to transmit information in a highly secure manner. Usually, the sender (Alice) encodes the secret key into some quantum states. She then sends these quantum states to the receiver (Bob), who will measure these states in sequence. Then, Alice and Bob communicate with each other about how they prepare and measure the quantum states using a classical communications channel.

"Based on this information, Alice and Bob can share a sequence of a common secret key," says Zhao. "Finally, they can compare some part of the secret key, and anyone who wiretaps the information within the quantum channel will be noticed by the users during this process." Security of their communications is guaranteed.

"With a 'decoy state protocol,' when our microlaser is being attenuated to the single-photon level, it can be used as a source in QKD," says Zhao. "Moreover, our laser can emit 4D qudits and transmit 2 bits/photon—doubling the channel capacity compared with qubits. Using 4D qudits in QKD can also allow more disturbance within the quantum channel—increasing the robustness of the communications system."

Next steps

The team is now focusing on three key areas to improve their microlaser system. Their first step is to integrate more on-chip ring resonators and waveguides to expand the system's dimensionality.

Second, they want to develop an electrical-pumped microlaser—their current device is optically pumped—to control all parameters in a fast, electrical way. "This step is critical to move our device toward real industrial applications," says Zhao.

And the third step is to develop a mature quantum communications system based on their device. "It'll consist of multiple hardware parts—including the microlaser as a source and the integrated receiver setup," Zhao adds. "We also want to develop the software parts based on the hardware parts to do the real quantum communication, and then we'll evaluate the robustness and bit rates of our system."

FURTHER READING

Z. Zhang et al., *Nature*, 612, 246–251 (2022); https://doi.org/10.1038/s41586-022-05339-z.

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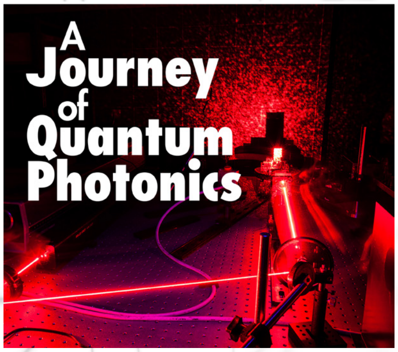

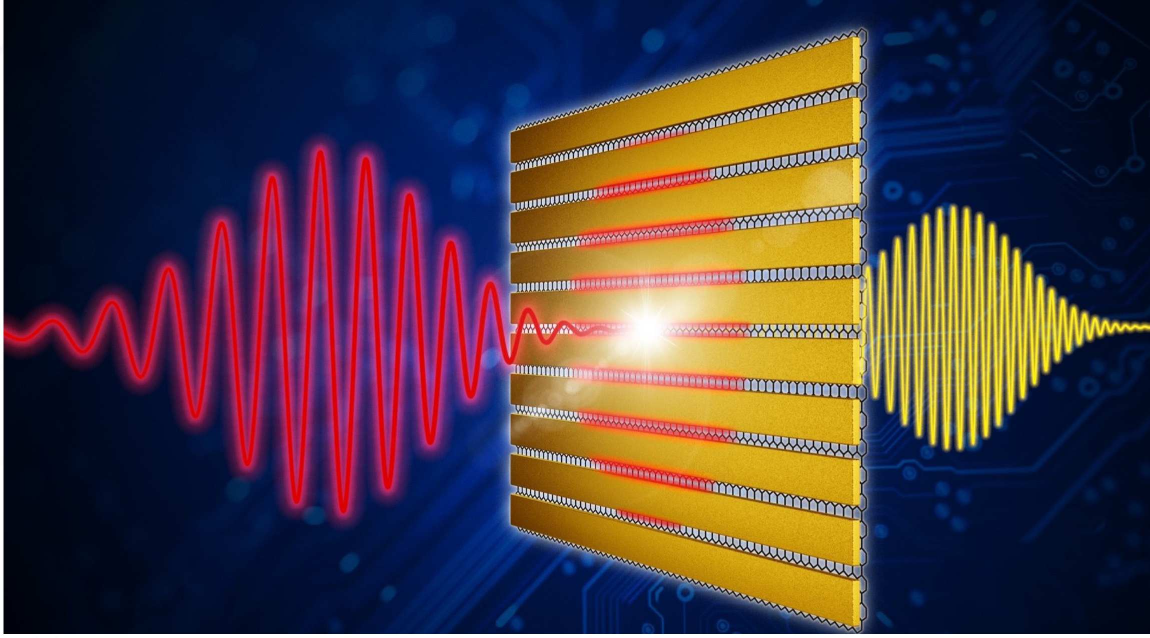

Schematic representation of harmonic generation by graphene with a metal grating.

CHAPTER 3:

Quantum materials for nonlinear terahertz photonics?

SALLY COLE JOHNSON, Senior Technical Editor, Laser Focus World

Quantum materials without a bandgap show extremely strong terahertz nonlinearities and can be enhanced for future 6G wireless systems with high data rates.

Several years ago, Klaas-Jan Tielrooij, a researcher at the Catalan Institute of Nanoscience and Nanotechnology in Spain, became intrigued by the fundamental properties of graphene and similar quantum materials—a bandgap of zero and massless charges. It turns out these properties are highly useful for electronic and optical devices.

The absence of a bandgap has rather unique implications for interactions between these materials and terahertz light.

“Terahertz light has a very small photon energy, so it doesn’t get absorbed by typical semiconductors, which have a bandgap larger than the photon energy,” says Tielrooij. “This inspired me to explore the suitability of these materials toward novel applications using terahertz light.”

At CLEO 2022, Tielrooij presented his work within this realm. It’s based on the concept that graphene and related materials like topological insulators conduct electricity in a special way and are highly efficient in upconverting terahertz photons to a higher photon energy—for example, creating 1.5 THz light from incident light at 0.5 THz.

The underlying mechanism is that these materials’ massless charges efficiently absorb terahertz light.

“Energy of this absorbed light is rapidly shared among all charges, which establish a hot carrier distribution, followed by subsequent cooling,” Tielrooij explains. “These processes take place on the femtosecond to picosecond timescale.”

These materials also exhibit terahertz nonlinearity: after terahertz absorption, they absorb less terahertz radiation. “As a result of the ultrafast heating-cooling dynamics of the electrons and their nonlinearity, terahertz light is generated with an increased photon energy, in particular 3-, 5-, or 7-times larger," he says. "This is the generation of the third, fifth, seventh, etc. harmonic signal."

Graphene and topological insulators not only exhibit intriguing physical properties, Tielrooij points out, but are also making their way into useful applications that exploit these properties not present in other materials systems. Terahertz harmonic generation is an important example of this trend because it can lead to electronic light sources with unprecedented frequencies in the terahertz regime (**see figure**).

"I find it fascinating that a single layer of electrons—either in graphene or at the surface of topological insulators—can lead to upconverting terahertz photons with a field conversion efficiency for third-harmonic generation on the order of 10% and the generation of 1 mW of third harmonic power," Tielrooij says.

The next step is to "keep improving the efficiency, while also designing devices that exploit the exceptional properties of these quantum materials toward nonlinear terahertz photonic applications," he adds. "One example is the possibility of electrically generating terahertz signals with carrier frequencies that were previously not attainable, such as for 6G wireless network systems."

RELATED READING

1. J. C. Deinert et al., *ACS Nano*, 15, 1145 (2021); https://doi.org/10.1021/acsnano.0c08106.
2. S. Kovalev et al., *npj Quantum Mater.*, 6, 84 (2021); https://doi.org/10.1038/s41535-021-00384-9.

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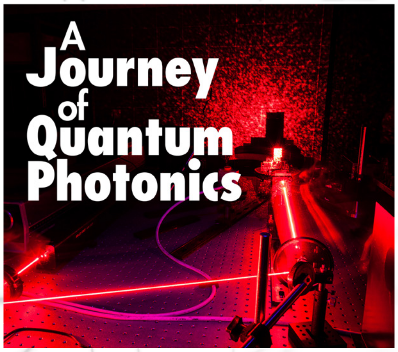

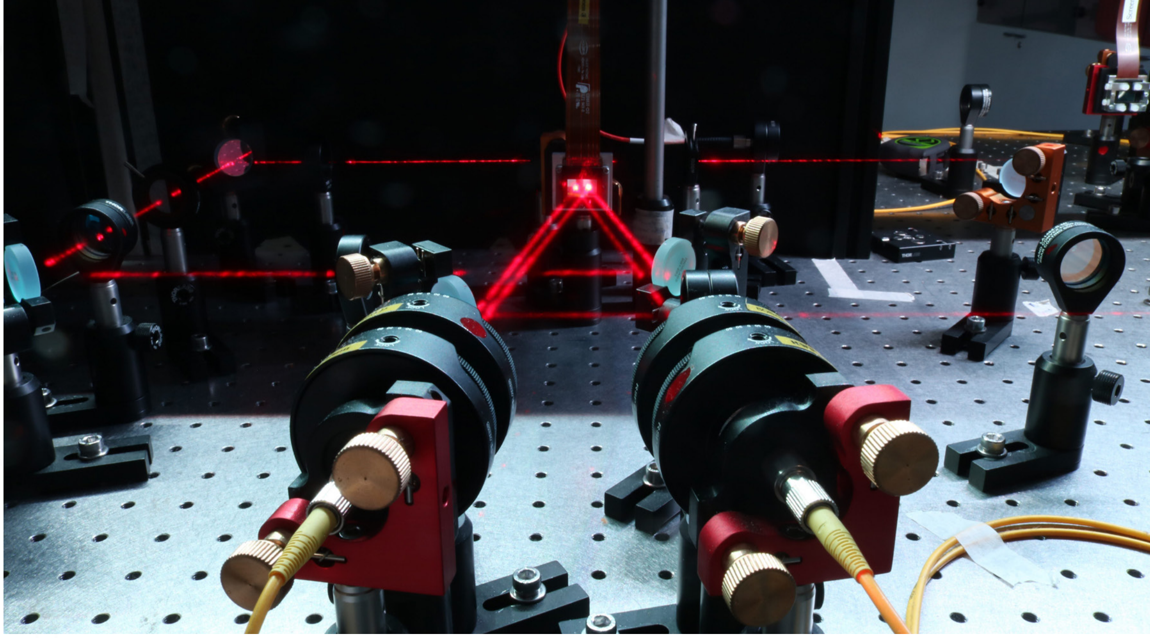

Spatial light modulator used to shape the structure of two photons to generated the desired quantum state.

CHAPTER 4:

Quantum light behaves differently than classical focused laser beams

SALLY COLE JOHNSON, Senior Technical Editor, Laser Focus World

> The Gouy phase for quantum light is not only different than its classical counterpart, its origin can be linked to another quantum state.

A group of researchers at Tampere University in Finland are exploring the anomalous behavior of focused light fields—an effect of the physics of optical waves—within quantum light. And they've shown quantum light with a well-defined photon number behaves differently than classical focused laser beams. This provides new insight about the phenomena and enables super-sensitive distance measurements.

After showing certain transformations of photon pairs can produce intriguing quantum states between the transverse structures of light beams, the researchers explored whether they could engineer a quantum state within a single beam of light so the beam could be used for quantum-enhanced measurements of different parameters.

"Our initial work resulted in quantum-enhanced measurements of rotation and when looking into how this concept could be extended to longitudinal and lateral displacements, we realized that, in the longitudinal case, the Gouy phase could be the driving force behind these measurements," says Markus Hiekkamäki, a doctoral researcher in the Experimental Quantum Optics group of the Physics Unit. "After delving into related literature, we discovered no one had really explored the effects of the Gouy phase on multiphoton quantum states and it led us to investigate the phenomenon in more detail."

Exploring light waves within the quantum domain

The first of the three main basic phenomenon involved is the Gouy phase, the phase anomaly of waves that occurs when a beam of light is focused. "We set out to explore this fundamental feature of waves within a quantum setting, the quantum Gouy phase," says Hiekkamäki.

The second concept they used for their experiment is photon bunching—a.k.a. Hong-

Ou-Mandel interference. It essentially means photons prefer to be in the same state because of their bosonic nature. “The effect of photon bunching into the same spatial modes enables us to generate the required photon number quantum states,” he says.

And the final important concept is the increased phase response of such states, which enables the researchers to resolve the faster and more complex evolution of the quantum state due to the quantum Gouy phase.

Within the quantum domain, the researchers found anomalous behavior speeds up compared to classical light. And thanks to Gouy phase behavior, which can be used to determine the distance a beam of light has propagated, the speedup of the quantum Gouy phase may help improve precision measuring of distances.

A tool for future application of quantum states of structured light?

Significantly, the researchers found that a link between the evolution of a classical mode of electromagnetic radiation and the associated quantum states can be quite straightforward, but powerful. “Our photons are simply propagating through a focus, but such a simple linear evolution added to the discussion of more than one fundamental topic—while also providing a tool for possible future application of quantum states of structured light,” says Hiekkamäki.

The most surprising aspect of this work for Hiekkamäki is that evolution of an N-photon number states is so similar to the “Nth harmonic” of the underlying mode. “Although simply reducing the wavelength of the light field doesn’t accurately model the evolution, if we also increase the transverse mode order and adjust the beam size, a classical light field has very similar behavior to the quantum state,” he says.

Next, the group is exploring new methods of measuring and characterizing complex quantum states of multiple photons, “which will hopefully allow us to improve the tools we have for working with structured quantum states of light and also enable other fundamental studies,” says Hiekkamäki.

FURTHER READING

M. Hiekkamäki et al., *Nat. Photonics* (2022); https://doi.org/10.1038/s41566-022-01077-w.

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