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A compendium of technical articles from *Laser Focus World*

PHOTONICS IN A NEW FRONTIER: SPACE

Growth within the photonics industry has been rooted in innovation and the willingness to embrace new technological challenges. Venturing into space is not something new for the photonics community. But space represents an expanded realm with exciting opportunities to test the capabilities of existing optical- and laser-based technologies, while also pushing the envelope to develop new ones.

Peter Fretty
Editor-in-chief

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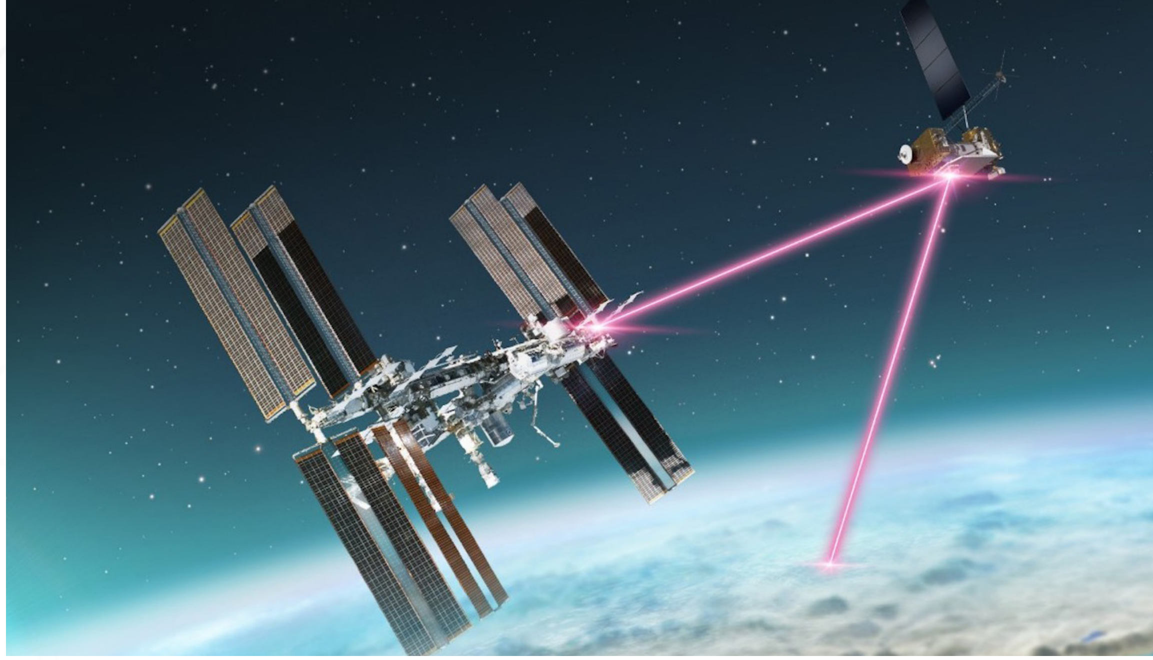

FIGURE 1. Illustration of LCRD relaying data from ILLUMA-T on the International Space Station to a ground station on Earth. *Nasa's Goddard Space Flight Center/Dave Ryan*

CHAPTER 1:

The era of infrared laser comms for space is upon us

SALLY COLE JOHNSON, Senior Technical Editor, Laser Focus World

NASA's Laser Communications Relay Demonstration (LCRD) project is currently putting optical communications to the test in space via a two-way infrared laser relay system.

More data bandwidth. Faster speeds. Decreased size, weight, power, and costs. Flexibility. Getting away from the overcrowded radio frequency (RF) spectrum. These are merely a handful of benefits infrared lasers and optical links can bring to transmitting information to and from spacecraft.

On December 7, 2021, NASA's LCRD project launched into geosynchronous orbit, 22,000 miles above Earth, hosted aboard the U.S. Department of Defense's Space Test Program Satellite 6. The goal: test the capabilities of laser communications as an alternative to radio waves, which have been used for space communications since the beginning of space exploration.

"After many years of people predicting optical comms was the way things are going in the future, we're now in the era of it's here," says Dave Israel, Laser Communications Relay Demonstration principal investigator for NASA at Goddard Space Flight Center. "Optical comms is past the phase of being a technology that 'may' be possible."

Laser comms

Why infrared lasers? Infrared beams can pack data into significantly tighter waves than RF systems, which means ground stations can receive more data in one downlink.

Optical comms involves sending a narrow beam from one location pointed directly at a receiver in another location (**see Fig. 1**), and an optical communications telescope's pointing must be extremely precise to reach its target—especially if it's thousands or even millions of miles away.

The LCRD payload is attached to a support assembly flight (LSAF), which serves as the backbone for LCRD's components (**see Fig. 2**). It has a star tracker and two optical modules to generate the infrared lasers that transmit data to and from Earth, and modems to encode data into laser signals attached to the backside of the LSAF.

LCRD's two independent optical communications terminals, each have their own optical module or telescope that's 10-centimeters in diameter. "They're each connected to their own modem," explains Israel. "There's also a bit of controller electronics involved, too: a computer system is connected to the optical module that does the most difficult part, the acquisition and the tracking, because narrow laser beams make it challenging."

The two optical communications terminals can each do their own bidirectional link to something on the other side. And a switch between the two terminals allows the data to be switched to go from one terminal to another. There's also a bidirectional RF link that the data can be switched to, if necessary, so it gets sent down to White Sands, NM.

"We're demonstrating the ability to do relay links, optical links, designed to send data to and from a user in orbit, which then gets relayed down to Earth," he says. "We use RF as a backup if the clouds or space junk are bad and we can't get the data down."

Although the optical relay is expected to help NASA reach higher data rates, "the most significant part of our mission is to get these links to work through the atmosphere, deal

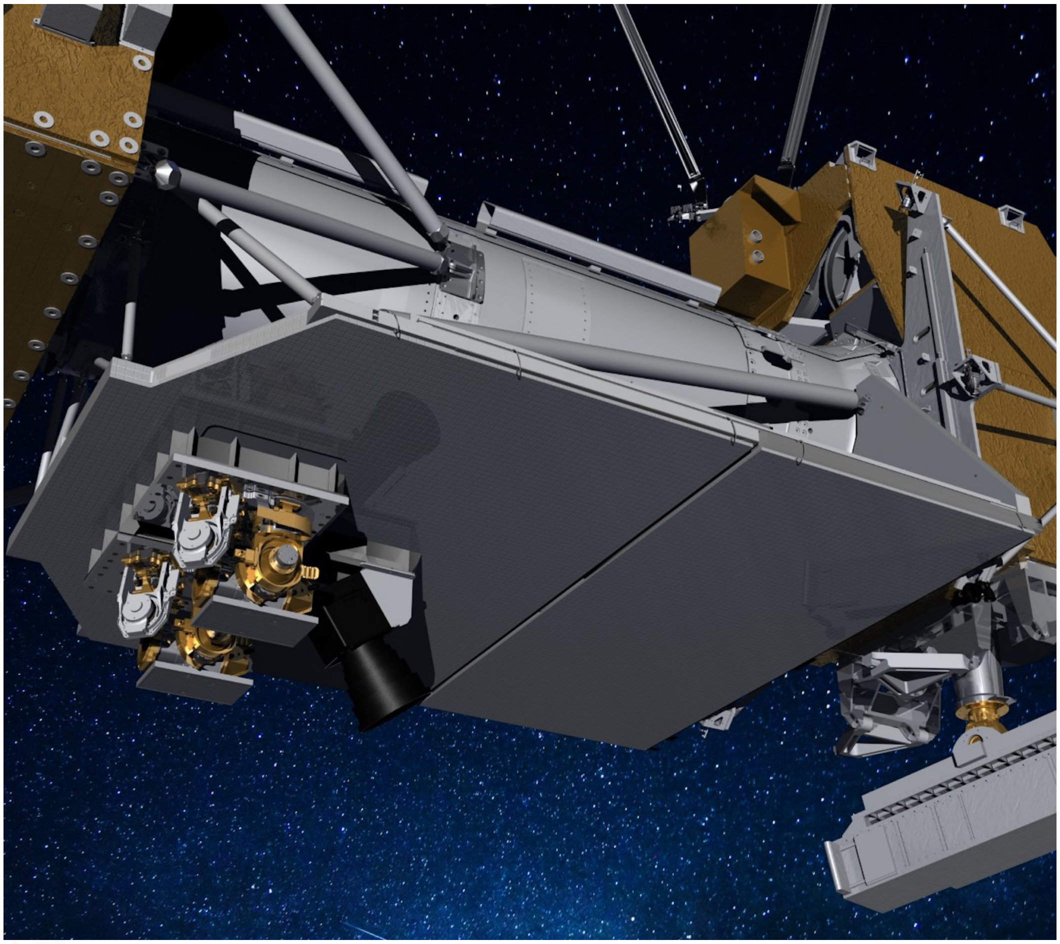

FIGURE 2. The LCRD payload is attached to an LCRD support assembly flight (LSAF), depicted in this illustration. *Nasa's Goddard Space Flight Center*

with weather effects, and get down to the ground station," says Israel. "We're working to demonstrate and understand how to communicate through the atmosphere as best we can when it's not cloudy, and when it is cloudy, to be able to predict and determine when to switch to a different ground station, and to understand all of these operational concerns."

Later in its mission, LCRD will serve as a relay between an optical communications terminal on the International Space Station (ISS) and ground stations.

Gaining operational experience

A Lunar Laser Communications Demonstration (LLCD) project flew to the moon in 2013, and it proved a laser comms system could be built to survive launch and operate in space, and do all of the pointing and tracking through the lunar orbit and the atmosphere and weather down to Earth.

"But it was a short-lived experiment, because part of the mission for the LADEE spacecraft orbiting the moon was for it to crash into the moon and make measurements of lunar dust," says Israel. "We proved the technology, but didn't get that much operational experience from it. So we have years, decades, of experience communicating to and from space using RF links, and it's sort of built into how we design and operate systems."

NASA doesn't yet have operational experience for optical links, so a key part of the LCRD technology demonstration mission is to gain it before using optical comms for an operational science or exploration application.

So far, they've established there's a certain point at which it's too cloudy to talk to the ground station or if space junk is in the way. But a key question now is how well NASA can predict when it's going to become too cloudy and plan in advance to switch to a different ground station, and how many ground stations are needed.

Benefits of optical comms

The first optical comms benefit most people tend to think of is achieving higher data rates— it provides more bandwidth to move data. "One of the real benefits for space missions is that exchange data rate, because for optical comms, involves a smaller wavelength than the RF systems," says Israel.

Decreasing size, weight, power, and costs are also big benefits. "It turns out, the size of the telescopes involved in space and on the ground are much smaller than the size required for an RF link," says Israel. "This reduces size, weight, and power, which is important on the spacecraft side to being able to build and launch it, but also on the ground side. Using a 1-meter telescope as opposed to an 18-meter large steel antenna really reduces the cost on the ground side to build and operate the systems."

Optical comms also provide the flexibility to switch to RF whenever necessary, which of course comes in handy when weather or space junk aren't cooperating.

And getting away from RF spectrum overcrowding and interference issues is another huge benefit of optical comms.

More NASA optical comms projects in the works

While NASA isn't quite ready to share in-depth details about LCDR's performance, results and a paper should hopefully be ready in Spring of 2023.

"There have been cases where the link has performed a little better than expected through the atmosphere. We're still refining our models and starting to see things we were

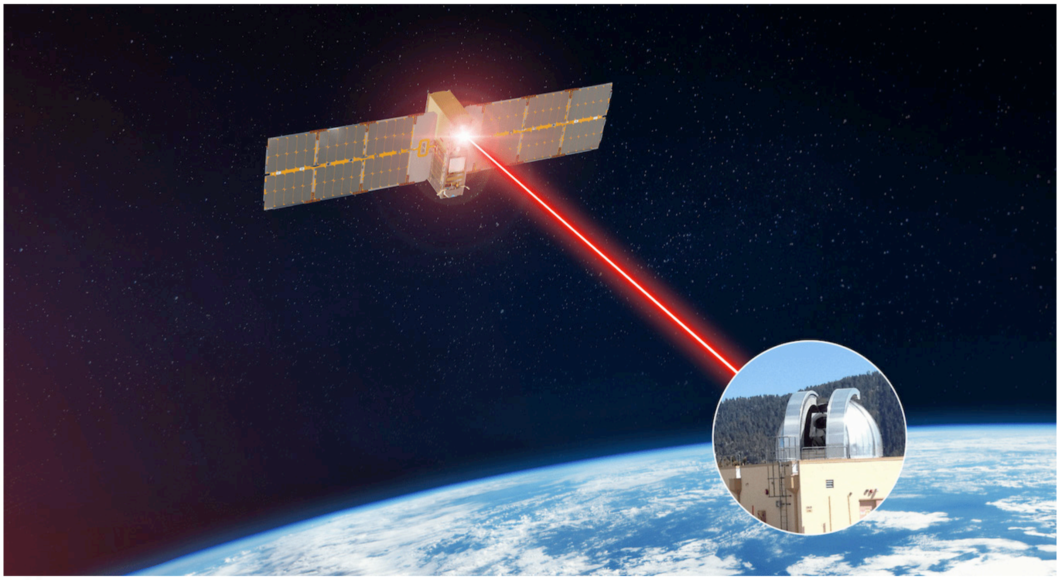

FIGURE 3. Illustration of TBIRD downlinking data over lasers links to Optical Ground Station 1 in California. *Nasa's Goddard Space Flight Center/Dave Ryan*

hoping to see from computer- and lab-based models," says Israel. "We're seeing some performance that's different than the predictions."

In 2022, a project called Terabyte Infrared Delivery (TBIRD) launched to showcase the high-data-rate capabilities of laser communications from a CubeSat within low-Earth orbit (**see Fig. 3**). TBIRD is about the size of a small lunchbox and will demonstrate its downlink at 200 Gigabits/s, which is much faster than possible in RF. It's also 200x faster than LCRD, and more than 100x faster than the highest fiber-optic internet speeds. These data rates will enable TBIRD to downlink large amounts of data in bursts as it passes over optical ground stations.

NASA also has an upcoming launch in 2023 of a payload called ILLUMA-T, short for Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal, which will fly aboard the International Space Station. It will gather data and send it to LCRD at 1.2 Gigabits/s. Once operational, LCRD and ILLUMA-T will be the first fully operational end-to-end laser comms system.

In 2024, the Orion Artemis II Optical Communications System (O2O) will take laser comms to the Moon aboard NASA's Orion spacecraft during the Artemis II mission. It's expected to transmit high-resolution images and video and will be the first crewed lunar flight to demonstrate laser comms, sending data to Earth at a downlink rate as much as 260 Megabits/s.

But that's not all—NASA also plans to boldly take optical comms into deep space and is currently working on a future terminal to explore how laser comms will fare against extreme distances and pointing constraints.

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Wireless power beaming will provide auxiliary power to increase the baseline efficiency of small satellites in low Earth orbit. *Image credit: Space Power*

CHAPTER 2:

Space-based wireless power grid operating via laser beams?

SALLY COLE JOHNSON, Senior Technical Editor, Laser Focus World

An on-demand laser 'auxiliary sun' may soon help power satellites and cut down on creation of space junk.

A new space infrastructure envisioned by Space Power, a UK company working with University of Surrey researchers to establish a wireless power grid in space, may soon enable an on-demand laser source as an "auxiliary sun" to beam solar power from satellites under solar illumination to small satellites orbiting closer to Earth during eclipse (**see figure**).

Satellites today rely on photovoltaic solar panels, which are semiconductor devices that convert sunlight into electrical energy. Some of this energy may be stored onboard on a battery so satellites can operate and can sustain themselves. The problem: this technology is designed to run exclusively from the power of the sun directly, even though satellites' low Earth orbit (LEO) can take them into the Earth's shadow.

Powered by space lasers

What does the new approach involve? A big piece of this work involves puzzling out which lasers will be most appropriate to transmit light over hundreds, if not thousands, of kilometers through space.

Laser light differs from sunlight in many aspects, but the most important difference in this case is it generates a very narrow band of wavelengths. "If we generate coherent light in a collimated form, it can be sent over large distances and remain a beam—and this is the key to using lasers to do this," explains Stephen Sweeney, a physics professor at the University of Surrey leading the experimental studies. "The laser beam is essentially delivering energy to its target, the satellite. In turn, its solar panels convert this light back into electricity for the operations of the satellite or to charge its battery. A series of energy conversions through the system translate into satellites having energy when they need it."

The researchers are also working to ensure the lasers they select and the light being generated are compatible with the photovoltaic solar cells on the satellites being targeted. Different types of solar panels exist, so they need to be able to accommodate this.

The group's transmitter will use lasers that can direct high-power beams toward a target satellite, but "it also requires optics and tracking to locate and send energy selectively to target satellites," Sweeney points out. "Essentially, the system starts with photovoltaic cells, which are a nice example of photonic technology themselves, and the electricity from it will be then converted into laser light for onward transmission."

It's important to note that the laser light must be a particular wavelength; it can't be a broadband white light like from the sun. "We're working on the choice of wavelengths and what the delivery of light needs to look like from the laser, and how it may tie in with the type of solar panel onboard the satellites," Sweeney adds.

Technology development is also underway on the laser side on pointing, optics for delivering it, communications between the satellites to know you're pointing in the right direction, and ultimately satellite targeting. "There are quite a few different aspects of optical system design involved in this project," Sweeney notes.

Weird space challenges, benefits

One space challenge is radiation, which can degrade solar cells and lasers, forcing researchers to place a heavy emphasis on reliability.

When a satellite is in the Earth's shadow, its operating temperatures can be cryogenic (a couple hundred degrees below zero). "From a mechanical perspective, satellites can cope with this," Sweeney says. "And an interesting thing about solar panels is that you actually get enhanced efficiency when they're in the eclipse and cool down. It's something we can take advantage of when we illuminate them with the laser while they're in an eclipse; we can get higher power generation."

Another challenge is that with the proliferation of satellites doing important work for humanity, LEO is becoming congested. The project's work offers a big benefit: helping increase satellite efficiencies will prevent the need to continuously send more satellites up than the mission really needs, which will cut down on the amount of space junk.

Light detection and ranging (lidar) technology is also poised to play a role tracking satellites and space junk, while laser-based communication in space is becoming more important. "It's becoming very clear that laser-based applications for space will be a big thing and, for the whole laser community, space is the next frontier to bring your technology," Sweeney adds.

Space Power is aiming for a prototype launch in 2023, with commercial operations planned for 2025.

This project is part of the $10 million (7.4 million GBP) United Kingdom Space Research and Innovation Network for Technology (SPRINT) program.

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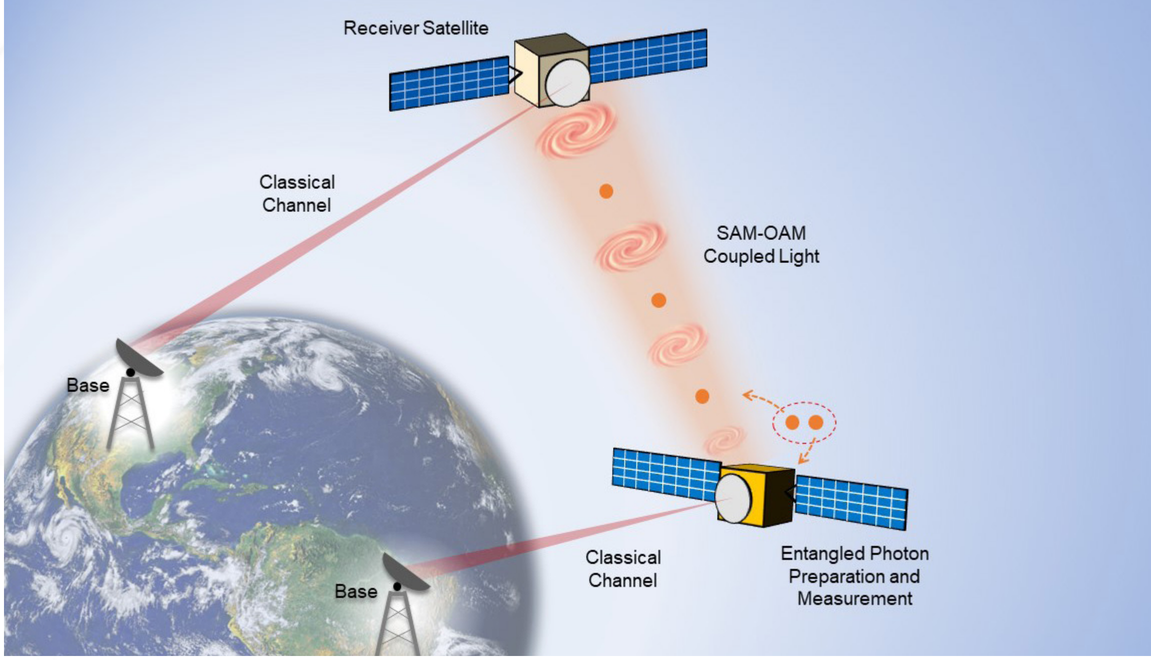

Image credit: Haoqui Zhao)

CHAPTER 3:

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,

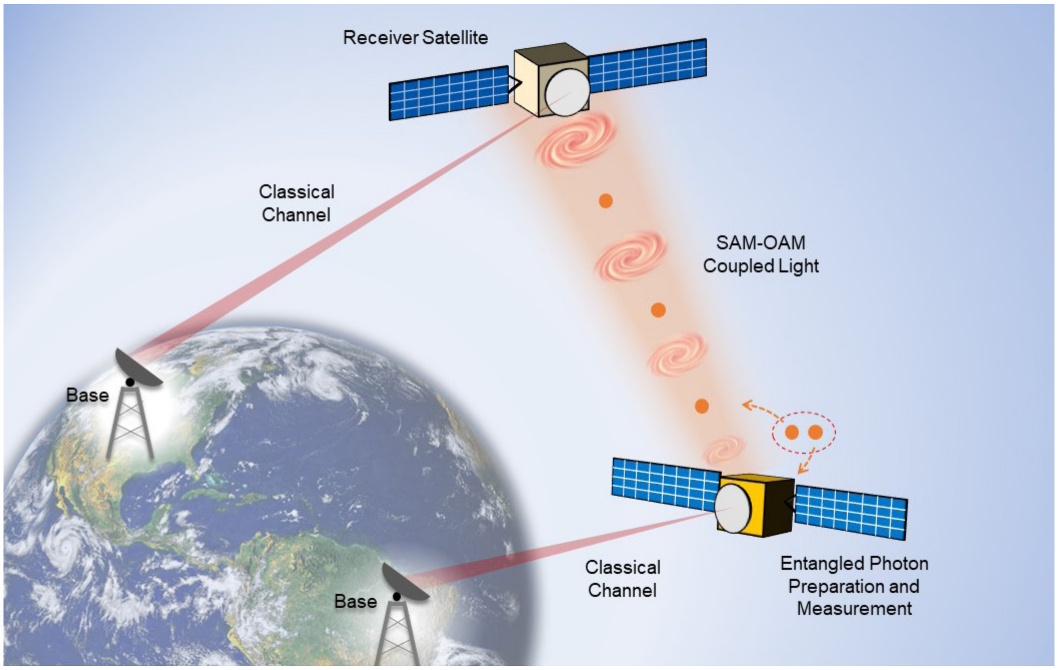

FIGURE 1. One potential application of the hyperdimensional microlaser chip is as a satellite-to-satellite high-dimensional quantum link. *Image credit: Haoqui Zhao*

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

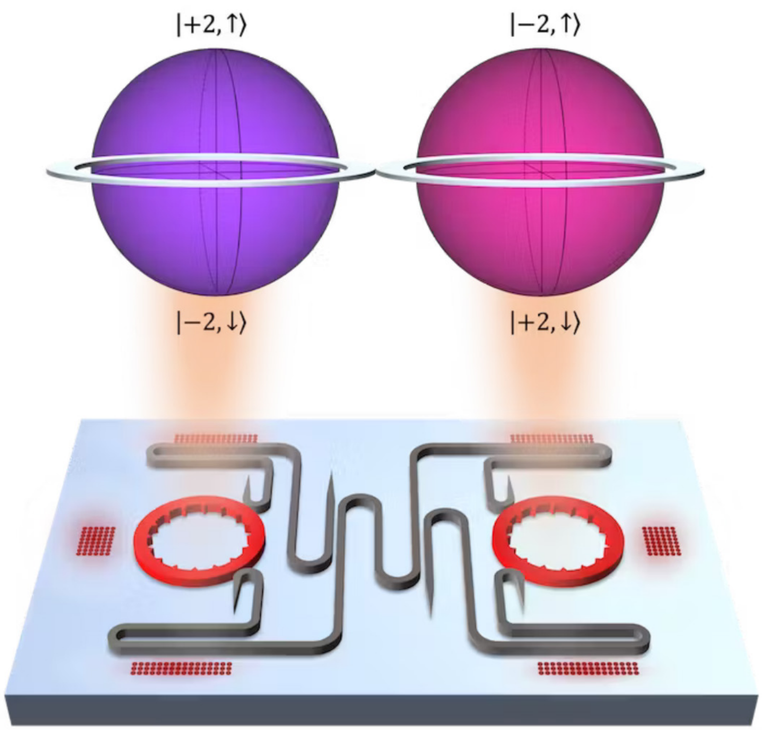

FIGURE 2. Illustration of the team's hyperdimensional microlaser chip, which generates qudits or photons with four simultaneous levels of information.
Image credit: Haoqui Zhao

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 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 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."

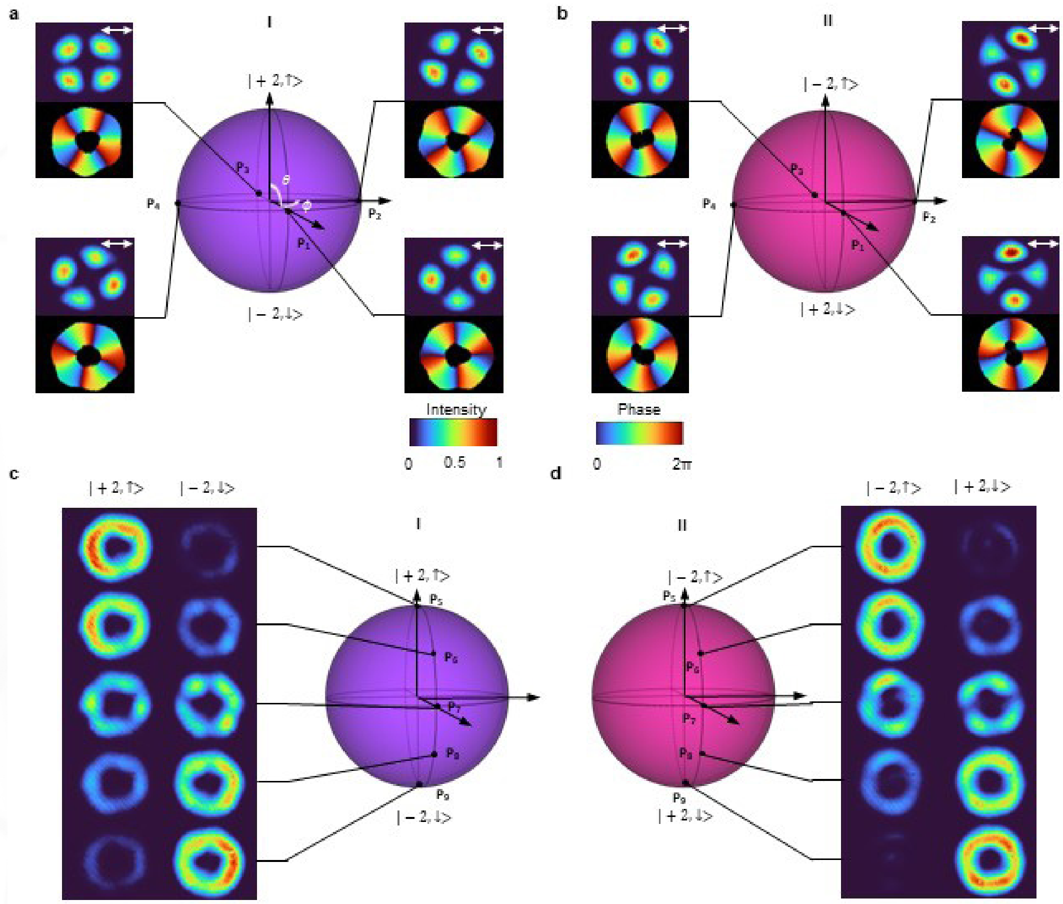

FIGURE 3. Arbitrary emission control on distinguished Bloch spheres (a geometrical representation of the state space of a two-level quantum mechanical system).

(Image credit: Zhifeng Zhang)

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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CHAPTER 4:

Design center investment looks to further commercialization of photonics in space

PETER FRETTY, Associate Group Publisher/Group Editorial Director, *Laser & Military*

Alter Technology announces a six-million Euro investment in photonics at the University of Strathclyde.

In mid-April, Alter Technology announced its decision to open a photonics design center in Glasgow at the University of Strathclyde. The driver? Accelerating the commercialization of photonics within two key growth markets—quantum and space. Alter is planning on making a significant investment over the next five years to fund R&D efforts focused on "quantum enabled positioning, navigation and timing systems, and photonic-based satellite optical communications."

According to the release announcing the investment, the location for the design center is strategic in that the Fraunhofer Centre for Applied Photonics and Strathclyde's Institute of Photonics—key partners for Alter Technology—are based within the same building, with the physics department teams nearby.

Laser Focus World had the opportunity to connect with Una Marvet, head of Alter's design center, to dig deeper into the commitment.

LFW: What do you see as the barriers to commercialization?

Marvet: The main barriers to commercialization are different for the two markets we're targeting—satellite communication (Sat Comms) and quantum position, navigation, and timing (PNT).

The main barrier for optical transceivers in Sat Comms arises from the relative immaturity of photonics technology in space harsh-environment applications. One of the key challenges is taking optical transceiver technology, which is widely used in terrestrial datacenter applications, and making it compatible with the SWAP and harsh environment and radiation requirements for space.

For quantum, a key barrier is to take the technology from research and university lab setups and package it into a reduced SWAP-C (size, weight, power, and cost) module. Traditional laser and quantum systems are bulky, sensitive to alignment, and costly. By combining volume semiconductor- and telecoms-style packaging and design techniques to produce laser modules for quantum technologies, we believe that we can offer a route to cost-effective real-world quantum applications.

The notable difference between quantum and space communications markets is of course the big question mark over exactly how quantum technologies will be realized and what their effect will be. There's a general feeling that there will be existential changes, but the picture of how the technology will be implemented and what the world will look like afterwards has yet to emerge. We're looking forward to being part of that.

LFW: How specifically will this center help address/alleviate the barriers?
Marvet: In order to solve these big challenges, we need multiple disciplines and skills from the telecoms, space, laser, semiconductor, and quantum industries to work closely together under the same roof and ecosystem. Bringing together the semiconductor and photonic manufacturing expertise and space application knowledge of Alter Technology with the laser and quantum expertise of Fraunhofer CAP and the University of Strathclyde will allow a completely new approach to how laser technology is used in space and quantum applications.

The mega trends related to resilient communications/increasing demand for bandwidth enabled by Sat Comms and the growing recognition of the game-changing potential of quantum technologies has undoubtedly provided momentum for this investment and the positive market outlook we see.

LFW: What would you say are the keys to success for the center?
Marvet: The key success for the center is to be the number-one or number-two supplier for optical transceivers into the harsh environment market and narrow linewidth laser modules for the quantum technology market.

This is an exciting time for both quantum and space photonics, and we're grateful to TÜV Nord for the opportunity to take advantage of Alter's existing capability and expertise and build on it to contribute fully to both markets.

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