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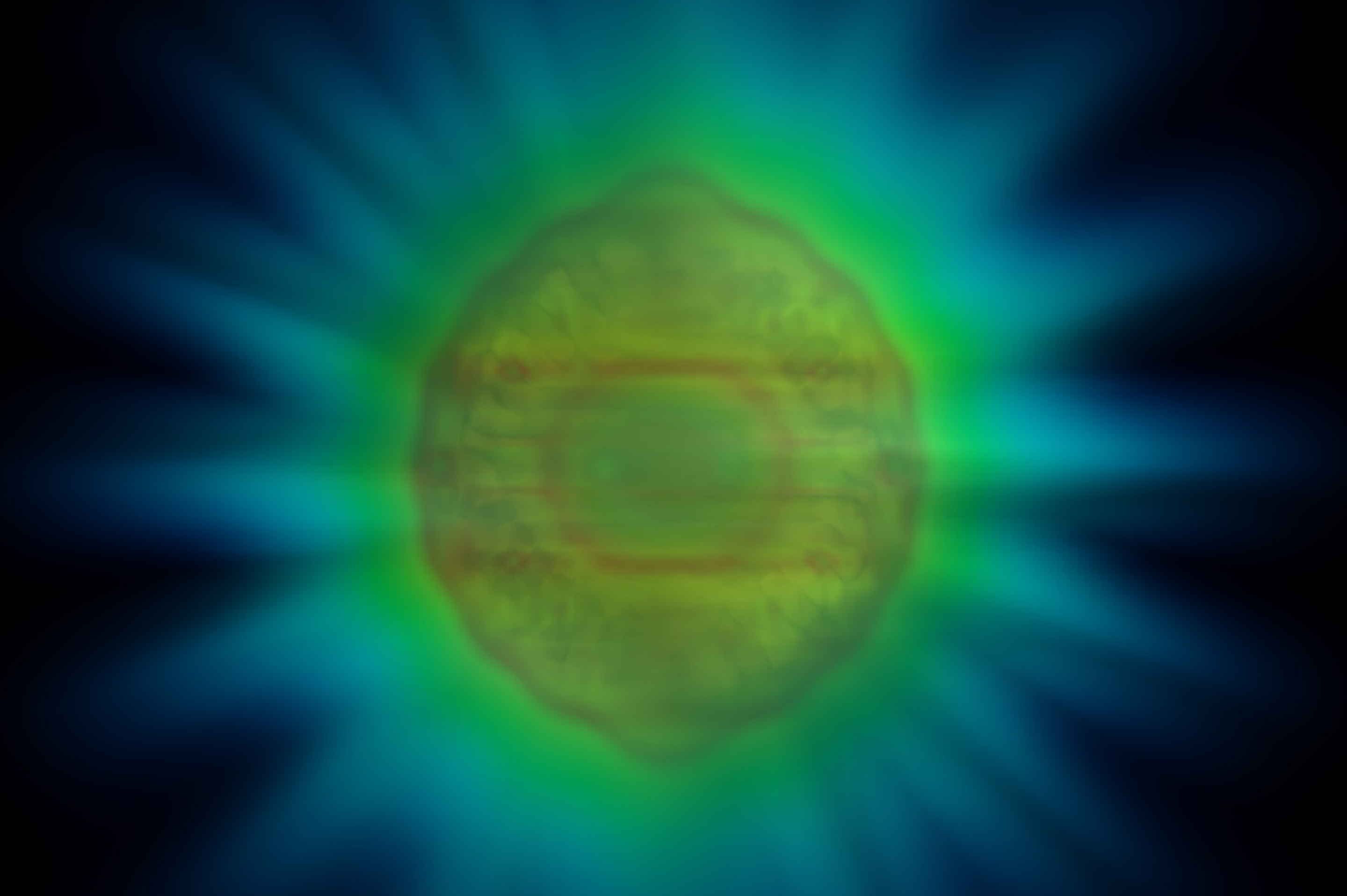

QUANTUM INNOVATORS

INSIGHTS INTO THE R&D INITIATIVES ENABLING TOMORROW'S QUANTUM APPLICATIONS

Winter 2024

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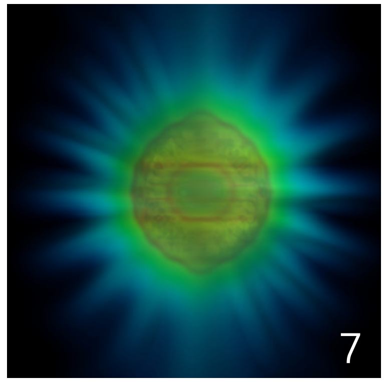

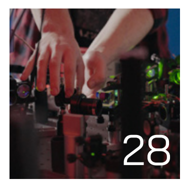

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Happy International Year of Quantum Science and Technology!

As we head into 2025, we'll be celebrating quantum innovations and advances all year long—thanks, in part, to the United Nations making it the International Year of Quantum Science and Technology. We'd be celebrating anyway, but it'll be more fun with the world along for the ride.

2024 brought some much-needed funding and progress—plenty of advances and innovation within the quantum realm. We just saw Google Quantum AI's Hartmut Neven, founder and lead, announce an impressive leap forward toward usable quantum computing via their quantum chip Willow, which can reduce errors exponentially while scaling up to using more qubits. Scaling is essential for progress, and they managed to crack a challenge the field has worked on for nearly 30 years.

In this issue of *Quantum Innovators*, Angela Demetriadou and Ben Yuen from the University of Birmingham in the U.K. share their cool quantum electrodynamics theory work to explain how light and matter interact at the quantum level. It highlights the power of visualizations combined with theory. With it, they made an image that shows the "shape" (expected intensity distribution) of a photon. A big thank you to them for sharing their work and the cover image with us.

We've got outstanding contributed articles for you—be sure to check out Michael Baczyk's piece about what's going on with quantum tech funding—and, as always, thank you to everyone for sharing your cool quantum work and news with us.

Happy holidays!

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Follow the money: Two stories of quantum tech investment

Three threads, three data sets, and two contradicting narratives. I'm about to walk you through quantum tech's funding story that can be read as both a bull and bear market case—depending on where you stand and how you connect the dots.

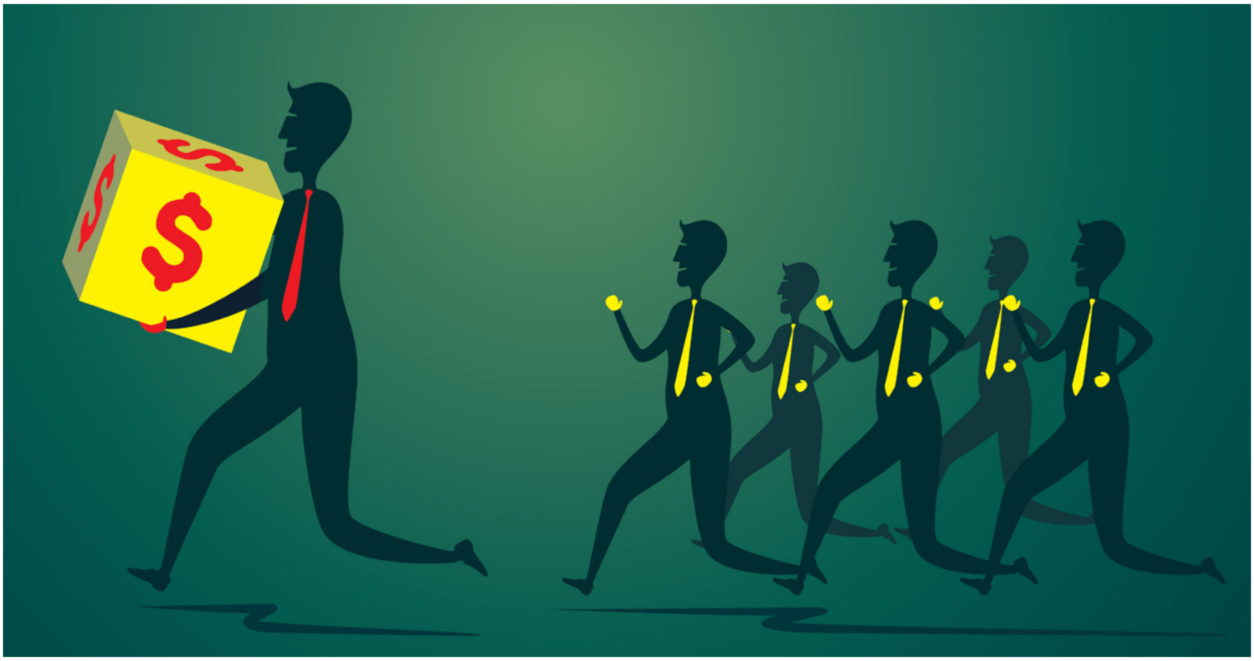
MICHAEL BACZYK

When isolated, even the most robust market data can tell opposing stories. This is particularly true within the quantum tech landscape, where government billions meet venture capital (VC) caution, and market consolidation either signals maturity or concern. Global Quantum Intelligence (GQI) can help detangle these threads and transform intricate market signals into actionable intelligence for your strategic decisions.

A money timeline: From NISQ gold rush to strategic patience

Looking at capital investment patterns (see Fig. 1) in quantum tech from 2020 through November 2024 (excluding national quantum strategies and major government programs like EIC, Horizon Europe, and DARPA), the data reveals a fascinating dichotomy. Our chart tracking \$7.06B total investment across 296 funding rounds shows remarkable resilience, with 2024 potentially hitting a record despite the broader tech market downturn.

But this apparent strength deserves closer scrutiny. PsiQuantum's \$620M commitment for its Australian facility comes with specific deployment conditions and timelines—bracketing just this deal reshapes the 2024 perspective entirely. The year's bar is constructed from a handful of large deals, while the proportion of smaller deals and diverse investments has notably shrunk compared to previous years.



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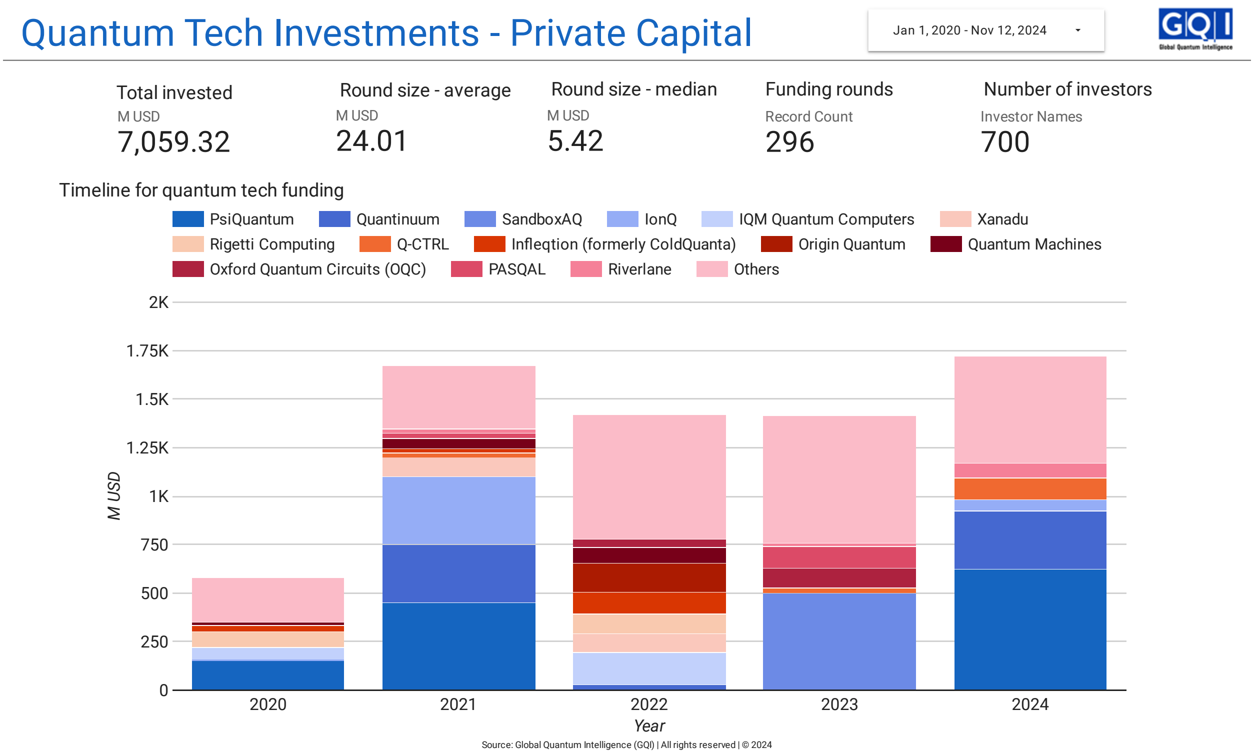


FIGURE 1. Quantum tech investment timeline (2020 to 2024). Investment of $7.06B across 296 funding rounds shows yearly distribution among major quantum players and smaller deals combined (excluding national quantum strategies and government programs).

Rounds are taking longer to close, but investors are doubling down where they see fundamental value: quantum hardware and midstack solutions. This shift from earlier "spray and pray" approaches to focused bets in 2024 is accompanied by steady investment levels in quantum sensing and communications and declining interest in pure-play software ventures. The median round size of $5.42M vs. an average of $24.01M illuminates this barbell strategy—continued support for early-stage innovation alongside concentrated bets on scale-up leaders.

Natural selection: Market exits, mergers and acquisitions, and power players

The quantum tech sector is experiencing its first wave of natural selection, with stark contrasts between market exits and strategic consolidation. As tracked by GQI, publicly traded quantum companies that went public via special-purpose acquisition company (SPAC) mergers reveal a worrying picture (see Fig. 2).

While IonQ maintains relatively stable share prices despite high volatility ($5.7B market cap), others frequently flirt with the $1 delisting threshold. Zapata's closure in 2024 marks the first high-profile market exit.

Yet simultaneously, the industry shows clear signs of maturation through strategic merger and acquisition (M&A) activities: IonQ's acquisition of Qubitekk, Kipu Quantum's purchase of Anaqor, and SandboxAQ's absorption of Good Chemistry signal the beginning of market consolidation.

The real industrial momentum is evident in manufacturing scale-up initiatives: IQM's fabrication facility in France, Diraq's partnership with GlobalFoundries, Quandela's photonic qubit manufacturing pilot line, PsiQuantum's utility-scale facility plans in Australia and the U.S., and Equal1's new center in Canada. With 57 on-premise quantum computer deployments totaling $1.22B in spending, the industry is decisively shifting from scientific exploration to engineering implementation. The quantum sector is entering its "crossing the chasm"

> Investors see fundamental value in quantum hardware and midstack solutions.

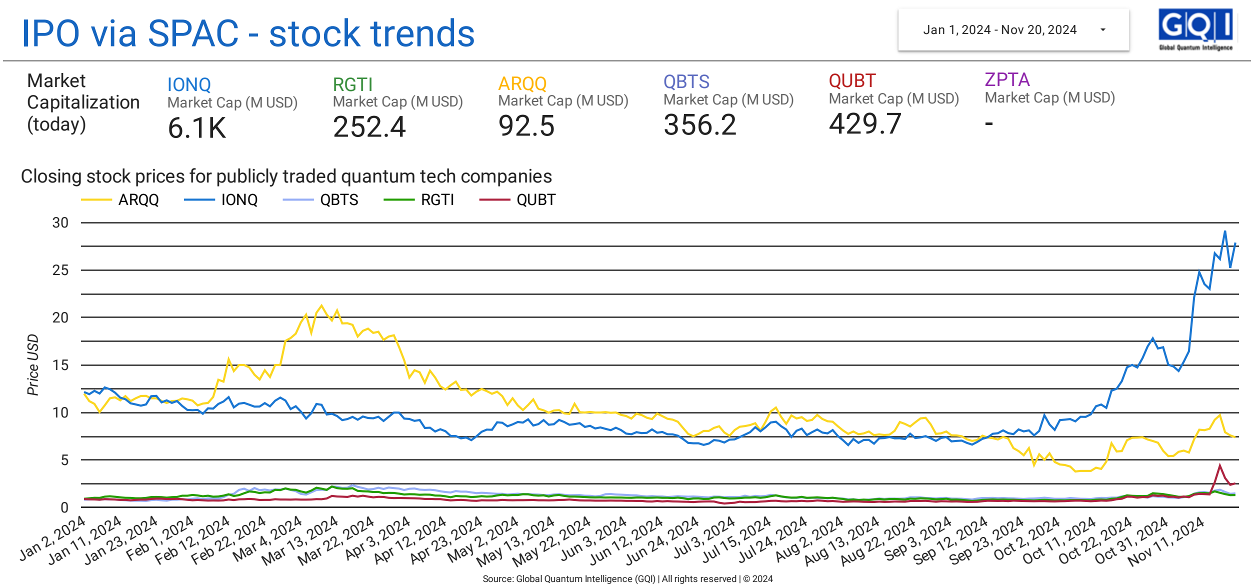


FIGURE 2. Public market performance of quantum companies for 2024. Stock price trends for quantum technology companies that went public via SPAC mergers show current market capitalizations and daily closing prices from January to November 2024.

moment—where winners and losers become more clearly defined through market performance and manufacturing capability rather than technical promises alone.

Value chain perspective: When money meets market reality—2025 to 2035

Market dynamics in quantum tech present a sobering reality check to the trillion-dollar projections frequently adorning startups' pitch decks. GQI's Total Addressable Market (TAM) Quantum Market Model (QMM) projections (see Fig. 3) reveal the immediate value capture is being driven by the quantum-safe cryptography transition—a fear-based but tangible market catalyst that the model shows will dominate the next five to seven years, and account for the largest share of realizable market value.

This defensive spending creates an interesting paradox: While the broader quantum computing promise remains speculative, the urgency to protect against its threat is generating real revenue today. Meanwhile, quantum enabling technologies—from cryogenics to photonics—maintain a steady 7% market share in GQI's projections, which demonstrates "picking and shovels" plays remain resilient regardless of which quantum computing architecture ultimately prevails.

> The quantum market's immediate value capture is driven by the quantum-safe cryptography transition.

Quantum sensing, targeting 10% market share by 2027, offers another path to near-term commercialization. The key insight for investors isn't about the absolute size of the quantum market, but rather understanding their addressable slice across time horizons. Our model shows quantum computing's inflection point in 2028 will require preceding infrastructure investment, particularly in quantum communications networks that enable modular architectures. Success in quantum tech requires matching your organization's capabilities to specific value chain opportunities rather than chasing headline market sizes.

The long view: Where public capital meets private ambition

The quantum technology investment landscape presents a fascinating study in contrasts— success metrics must be viewed through multiple lenses simultaneously. The apparent dichotomy between private market caution and technological momentum could be bridged by strategic

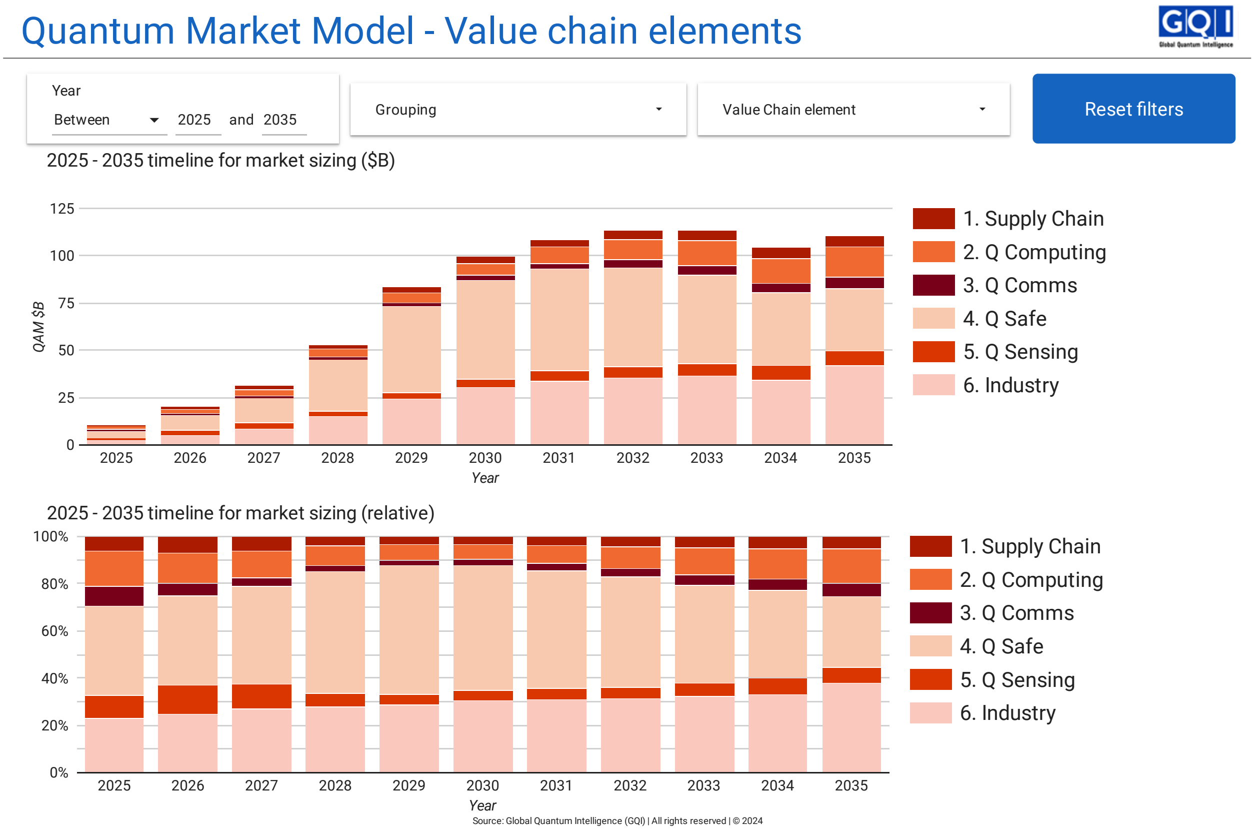


FIGURE 3. GQI Quantum Market Model value chain projections for 2025 to 2035. GQI's QMM dissects the total addressable market (TAM) across quantum technology value chain segments and reveals shifts in relative market sizes over time.

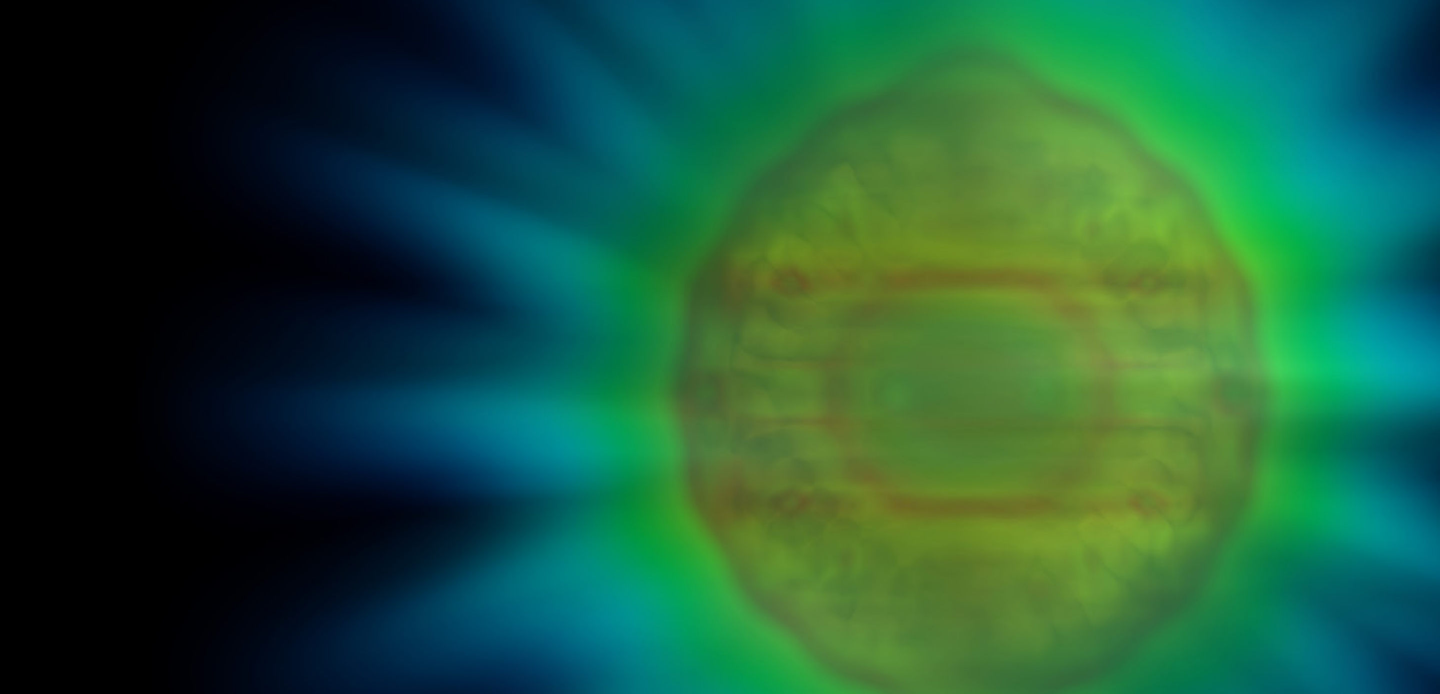
public funding, which is historically the key enabler for emerging technologies crossing their "valley of death."

While private capital is becoming more selective and concentrated, evidenced by the barbell investment strategy and market consolidation through M&As, the quantum sector's fundamental trajectory remains strong, backed by $1.22B in quantum computing on-premise deployments and aggressive manufacturing scale-up initiatives.

GQI's Market Model suggests that both near- and long-term value capture opportunities exist across quantum technologies. The elevated status of quantum technology on national agendas—driven by technological sovereignty concerns, security implications, and its increasingly recognized dual-use potential—further reinforces its strategic importance.

The key to navigating this complex landscape lies in understanding that public funding isn't merely a stopgap, it's the essential catalyst that can transform today's technological promises into tomorrow's market realities while securing national strategic interests.

Michael Baczyk is the director of investment advisory for Global Quantum Intelligence (GQI), a business intelligence firm for quantum technology (New York, NY and London, U.K.); e-mail: michael@global-qi-com; https://global-qi.com.



Quantum electrodynamics theory unveils precise 'shape' of a single photon

New theory developed by Angela Demetriadou and Benjamin Yuen at the University of Birmingham in the U.K. explains how light and matter interact at the quantum level—at last!

SALLY COLE JOHNSON, EDITOR IN CHIEF

In what led to a breakthrough for quantum physics and photonics, Angela Demetriadou, a professor of theoretical nanophotonics, and Benjamin Yuen, a research fellow in theoretical quantum nanophotonics, set out to answer a fundamental question: How are photons really emitted by atoms and molecules, and what effect do their geometry and the optical properties of the environment have on them?

Physicists have searched for an answer to this question for a long time but, until now, it could only be answered with simplified models. The team's work enables precisely defining how a photon interacts with matter and other elements of its environment.

"I recall a discussion about this with my Ph.D. supervisor Professor Ed Hinds of Imperial College, London, more than a decade ago, and it's lingered over me ever since," says Yuen. "When I first met with Angela, I realized that with our combined expertise we were onto something."

Recently, there's an increased interest in coupling experimentally quantum emitters—whether fluorescent molecules, quantum dots, etc.—to open nanophotonic systems. "But most of the theoretical

The "shape" (expected intensity distribution) of a single photon emitted by an atom on the surface of a silicon nanoparticle. (Image credit: Benjamin Yuen) descriptions we had available to us so far to describe the light-matter interactions were either phenomenological or making assumptions that were limiting our understanding of the processes involved and some experimental findings," says Demetriadou.

So they created a rigorous theoretical description for these interactions "to gain greater understanding of these light-matter interactions to see how they can be used for quantum technology applications with new nanophotonic systems," Demetriadou says. "Ben did a remarkable job in developing the theory, and we got a lot more out of it than we expected."

Quantum dynamics

It started by trying to "describe the quantum dynamics of an atom, molecule, or any other simple quantum emitter with the resonant modes of a photonic nanostructure," explains Yuen. "Classically, such photonic resonances are well known but their quantum dynamics was a problem we felt we needed to solve."

In quantum terms, things appear less concrete. There is a quantum state or 'wavefunction' that instead describes the system. It accounts for all possible paths along which the system evolves and how these interfere with one another.

"For the electromagnetic field in isolation, the classical and quantum behavior can be remarkably similar because Maxwell's equations embrace interference and free photons don't interact, but when an atom or other quantum emitter is involved it can be drastically different," Yuen says. "In some ways the atom is like a conduit for the energy to excite many more light modes, while it can also enter into a cycle of emission and reabsorption that cause the photon's existence to pulse on and off." (See video.)

This complexity has meant most models consider a much simpler version of these kinds of systems. While these models are very effective for describing macroscopic situations like an atom within a high finesse cavity, "nanophotonic systems aren't so clear-cut: They have many broadband and overlapping resonances, radiate efficiently to the far field, and there is no clear boundary between 'inside' and 'outside' like you have with a cavity," Yuen points out.

The team's first task was "to combine the machinery of quantum field theory with all the details provided by classical electromagnetism to produce a complete and exact theory. Once we did this, we then had to figure out a way to solve the quantum equations of motion using finite computational resources," Yuen adds.

Main takeaways

First, visualizations are useful to physicists and everyone else. The image the team made may be aesthetically pleasing but, together with the rest of their theory, it shines a spotlight on what's really going on within a somewhat esoteric process.

Second, Demetriadou and Yuen welcome the new era of quantum and photonic engineering with open arms. Studies like theirs provide the tools to harness quantum mechanics in new ways that when combined with photonic engineering can change the way we communicate securely, detect pathogens, or harvest energy from light, to name merely a few.

"Our work is applicable to other research areas, such as controlling photochemical and photocatalytic reactions with nanophotonic devices, which involves the quantum interaction of molecules with nanophotonic environments," says Demetriadou.

Finally, they hope to inspire a fresh, more global interpretation for quantum mechanics. "By embracing the complexity of the environment, we showed an excited atom decays just as radioactive atoms that trigger the demise of Schrödinger's cat," Yuen says. "But in our case, we didn't need the controversial 'wavefunction collapse' caused by an observer. By building better quantum models, we may just find that the randomness of quantum mechanics is instead replaced by complexity and chaos."

As with most groundbreaking work, they encountered cool surprises along the way. "Quite amazingly, several details just started to drop out of our theory, such as exactly how light propagates to the far field, and exactly what the shape of the photons' intensity distribution is expected to be," Yuen says. "This was surprising because we didn't explicitly specify these characteristics—they appeared because we incorporated a complete set of solutions to Maxwell's equations into our quantum model. It was also very reassuring that we were on the right path."

Yuen was also quite astonished when he realized their theory describes all the dynamics of an "open quantum system," which is incredibly difficult to achieve without making significant approximations.

Quantum theory challenges

Demetriadou and Yuen faced two clear challenges to overcome with their theory. First: Write down an accurate quantum theory of a seemingly lossy photonic system that radiates energy to the far field. And once they had this quantum theory, they had to make it tractable without needing to solve the energy exchange between the atom and each one of the infinite light modes present within the continuous frequency spectrum.

The first challenge they faced was to avoid the many pitfalls encountered when considering quantum systems that lose energy through radiation. "To navigate around these we instead considered the entire universe as one closed but infinitely large system," says Yuen. "But by doing so, we gave ourselves the second challenge: A need to solve a continuum of possible interactions between the atom and each frequency mode of light within a continuous spectrum."

They found a way to transform the continuum of possible interactions into a discrete set of them.

Ben Yuen with his whiteboard. (Photo credit: Benjamin Yuen)

"We used a branch of mathematics known as complex analysis to transform the problem from a continuous set of real valued frequencies into a discrete set of complex valued ones," explains Yuen. "This provided an enormous simplification of the problem and allowed us to precisely represent the problem using just a few hundred of these 'complex' light modes."

Ultimate goal now? "To build a numerical tool to solve the quantum electrodynamics for any nanophotonic system, regardless of its material properties or shape," says Yuen. "Ideally we'd like to build a complete computational package that allows engineers to quantize and solve any nanophotonic system in a user-friendly way. Our work provides a big step in this direction, which ultimately will unlock a new generation of quantum photonic engineering."

FURTHER READING

B. Yuen and A. Demetriadou, *Phys. Rev. Lett.*, 133, 203604 (Nov. 14, 2024); https://doi.org/10.1103/physrevlett.133.203604.

Near-field energy transfer provides route to ultrahigh-density solid-state optical memories

A combined framework of quantum electrodynamics and quantum mechanical electronic structure theories reveals a promising pathway to exceed the current limitation on data storage.

SWARNABHA CHATTARAJ, SUPRATIK GUHA, AND **GIULIA GALLI**

With the ever-increasing demand of computational power and memory capacity, we are facing an imminent information bottleneck. As we move from the dimensional to the functional scaling era, it is critical to design novel platforms for information storage and processing.

We propose a new paradigm for an all-optical solid-state memory. In traditional optical memories such as DVD and Blu-ray devices, the volume where a single bit can be stored is limited by the diffraction limit of light. We envision overcoming it by exploiting a dense ensemble of point defects within solids as the information storage medium.[1] Specifically, we consider rare earth (RE) ion impurities within an oxide as storage medium.

RE are elements with partially filled and optically active 4f electrons. These 4f electrons are shielded from the environment by the outer filled electrons, which make the RE ions robust against noise and suited for device-level implementations.

For a typical doping concentration, a μm^3 volume of material can comprise 10 million RE ions. Each RE ion exhibits slightly different optical emission and absorption energies due to local variations of the crystal field of the host, and each ion can be addressed individually using a narrowband tunable laser, leading to a potential $\sim 10^{18}$/cc bit density, comparable to DNA storage. Such density is higher than that of 3D flash memories, the densest memories available today, by 1,000-fold.

The storage of the bits can be achieved by transferring an optical excitation from the RE ion to a nearby defect in the host crystal, for example an oxygen vacancy or substitutional site. Such transfer processes can occur by nonradiative resonant energy transfer (NRET), and they provide a means to trap excitations into long-lived excited states acting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as memory bits. These excited states can then be read out by probing the effect of the energy transfer process on the RE, for example, by optical measurements of the energy or polarization shift of the RE ion (see Fig. 1).

The design of the memories presented above was conceived using a first-principles theoretical and computational framework to understand, qualitatively and quantitatively, NRET processes between defects in solids. By "first principles" we mean the results can be acquired by knowing only the atomic positions within the materials and adopting theories rooted in quantum mechanics—without any need to fit experimental data.

Conventionally, the near-field energy transfer processes between a source and an absorber have been modeled by dipolar transitions between two level systems. However, defects within materials are more complicated. Quantum mechanically, the ground and excited states of the defects are described by many electron wavefunctions, including spin degrees of freedom of all the electrons of the source and absorber. But a detailed quantum mechanical treatment of NRET processes in solids has so far been lacking.

To address this gap, we developed a framework integrating, on the same footing, nonrelativistic quantum electrodynamics (QED) and first-principles electronic structure calculations based on density functional theory (DFT). We describe the light-matter interaction in a form that includes orbital motion and spin degrees of freedom of many electrons at the same time. It allows us to account for the many-body nature of the defect states, and we are able to estimate the rates of the spin-flip and spin-conserving processes individually.

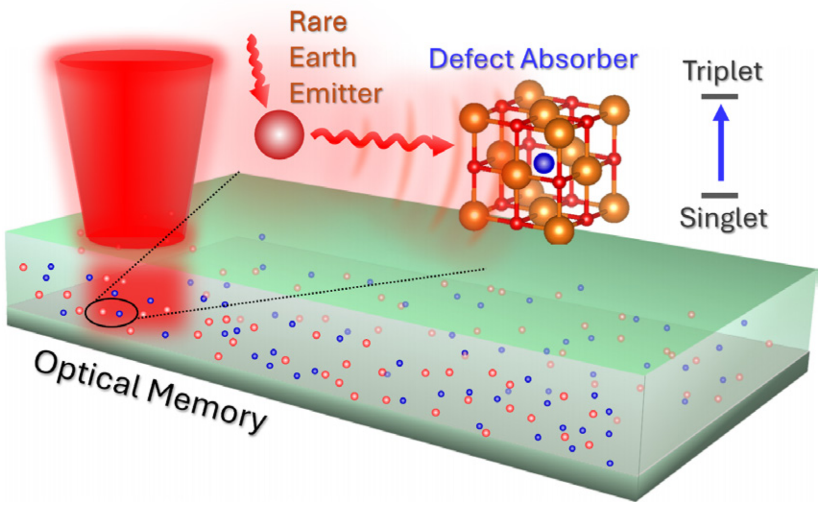

FIGURE 1. Depiction of the ultrahigh-density optical memory. Red dots represent rare earth ion impurities, and blue dots represent defects onto which the excitation is stored by using near-field energy transfer processes. Many optically addressable RE ions within the diffraction-limited excitation volume (red beam) result in an enhanced bit density.

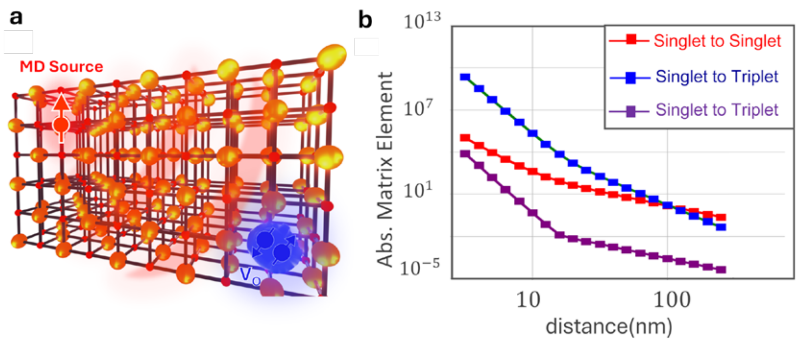

FIGURE 2. (a) represents the near-field energy transfer processes from rare earth (RE) ion to an oxygen vacancy within MgO. The electronic structure of the vacancy (V_0) is obtained from first-principles calculations, and it includes the spin degrees of freedoms. (b) shows the calculated absorption matrix element of V_0 as a function of distance from the source. The blue and violet curves represent transition to the spin 1 and spin 0 triplet states, respectively. The result indicates that a singlet-to-triplet transition becomes stronger than the singlet-to-singlet transition at small separations of ~10 nm.

Spin-flip transition at near field

We use our theoretical framework to study an exemplary system: a magnesium oxide (MgO) solid with a neutral oxygen vacancy, also known as an F center (absorber), and implanted RE ions (source). MgO is considered a good host material for spin defects due to its low nuclear spin noise, and the F center is a common and well-understood point defect. The ground state of the F center has two electrons occupying orbitals residing within the band gap of MgO in a singlet configuration; i.e., with zero total spin. An excited state is formed when one of the electrons is excited from a defect orbital resulting in either a singlet excited state (zero spin) or a triplet excited state (spin 1).

When a far-field photon source, such as a source at a large distance from the defect (e.g., oxygen vacancy or F center), is used for the transition from the ground to an excited state of the F center, only the transition to the singlet excited state is allowed. But when the photon source is in the near field, close to the F center, a transition from the singlet ground to a triplet excited state is not only allowed but can even be stronger than the singlet-to-singlet transition. Such a singlet-to-triplet transition involves a flip of the spin of the electron, which is forbidden at far field (see Fig. 2). It means this triplet excited state can potentially be long lived and used as a memory bit.

Outlook

To enable the design of the ultra-dense optical memories envisioned in our work, we need to enable near-field energy transfer between rare earth impurities and defects, which is responsible for activating spin to triplet long lived transitions. Such transfer requires control over the average spacing between the REs and the defects. A critical parameter to determine is the distance at which the probability of the energy transfer is above of 50%. For the case of the F center within MgO, this distance is found to be a few nanometers—a realistic separation in solid-state systems. Our systematic study not only enables finding such distance parameters but also provides ways to map them as a function of the angle between the RE and the defect.

We emphasize that the NRET processes are ubiquitous within defective semiconductors and insulators, and so they play a role in other quantum technology platforms based on defects within solids. Our framework provides a viable path to a much-needed quantitative understanding of such platforms.

REFERENCE

1. S. Chattaraj, S. Guha, and G. Galli, *Phys. Rev. Res.*, 6, 033170 (2024); https://doi.org/10.1103/physrevresearch.6.033170.

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PHOTONICS BREAKTHROUGH can drastically shrink quantum computing parts

Very thin materials can create entangled pairs of photons to be used as quantum bits

LEEVI KALLIONIEMI AND **XIAODAN LYU**

Many quantum computers use electrons as small switches called quantum bits, or qubits, to perform numerous calculations simultaneously. By using quantum computers, we could resolve complicated calculations within minutes instead of millions of years, which today's supercomputers would need.

The benefits of such high-speed computing are staggering. We could discover new drugs much faster, for example, and better understand the complexities of climate change by harnessing the ability of quantum computers to perform calculations and discover patterns within large data sets quickly.

But there is a challenge: For electron qubits in quantum computing to work, they require ultracold temperatures close to the coldness of outer space.

An alternative is to use light particles, or photons, which can function as qubits at room temperature—they could be cheaper, simpler, and more practical than using electrons.

For photons to become qubits, the light particles must be produced in linked or entangled pairs so that what happens to one photon affects the other instantly, no matter how far apart they are.

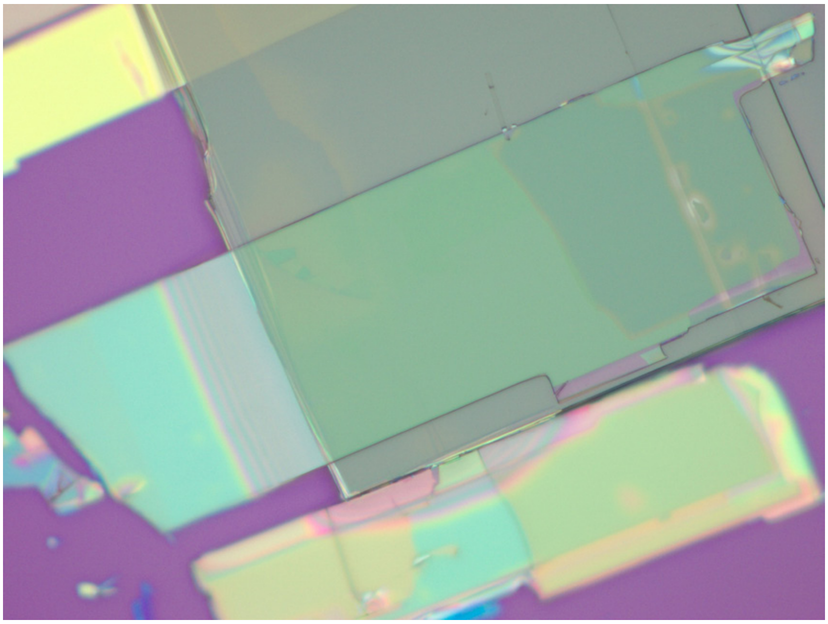
A crucial requirement for entanglement is that photon pairs must vibrate in sync. One way to do this is to shine a laser on millimeter-thick crystals and use optical equipment to maintain the link between the photons. But such a setup is too big to integrate into a computer chip, which limits its usefulness.

Our team at Nanyang Technological University, Singapore (NTU Singapore), led by Professor Weibo Gao, found a way to address this issue by using much thinner materials that are micrometers thick.

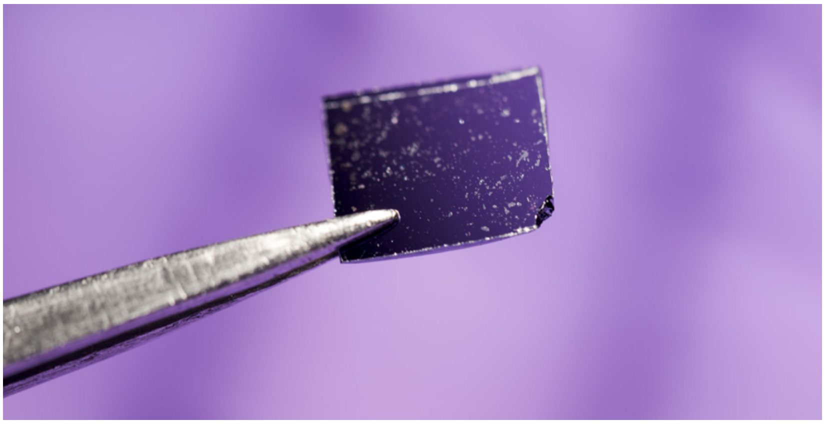
This could shrink quantum computing parts by 1,000x and make devices for quantum applications—such as quantum information and photonic quantum computing—more compact and simpler by eliminating the need for bulky optical gear.

The quest for thinner materials

Scientists have sought thinner materials to generate photons as qubits,



Two thin flakes of niobium oxide dichloride stacked on each other and photographed under a light microscope. One flake's crystalline grain (gray flake) is positioned perpendicularly to the grain of the other flake (green flake). (Image credit: NTU Singapore)



Flakes of niobium oxide dichloride on a sample holder. (Image credit: NTU Singapore)

but this is difficult because when materials get thinner their photon production rate falls, which makes them impractical for quantum computing.

But scientific advances in recent years found a crystalline material called niobium oxide dichloride ($NbOCl_2$) that holds promise. The material has unique optical and electronic properties and can produce photon pairs efficiently, even though it is merely micrometers thick. One major problem is the photons it generates are still not entangled and cannot be used as qubits.

We discovered a way to tackle this.

Inspiration from the past

Gao, from NTU Singapore's School of Electrical & Electronic Engineering and School of Physical & Mathematical Sciences, theorized that an established method to produce linked photon pairs with larger crystalline materials could be applied to thinner $NbOCl_2$.

The existing method, published in 1999, stacks two flakes of thick crystals together. The crystalline grains of each flake are aligned perpendicularly to each other before a laser is shone at the crystals.

But the photon pairs produced in this way can still vibrate out of sync because of the way they travel inside the bulky crystals. As a result, optical equipment is needed to synchronize the light particles to ensure they become entangled. Aligning the optical gear to do this can also get cumbersome.

If niobium oxide dichloride flakes are used instead, Gao believed the photons created would travel a shorter distance inside the thin flakes because they are much thinner than the bulkier crystals from past research. This would cause the photons generated within the thin flakes to become synchronized and entangled—without using extra optical equipment to ensure the photons were linked.

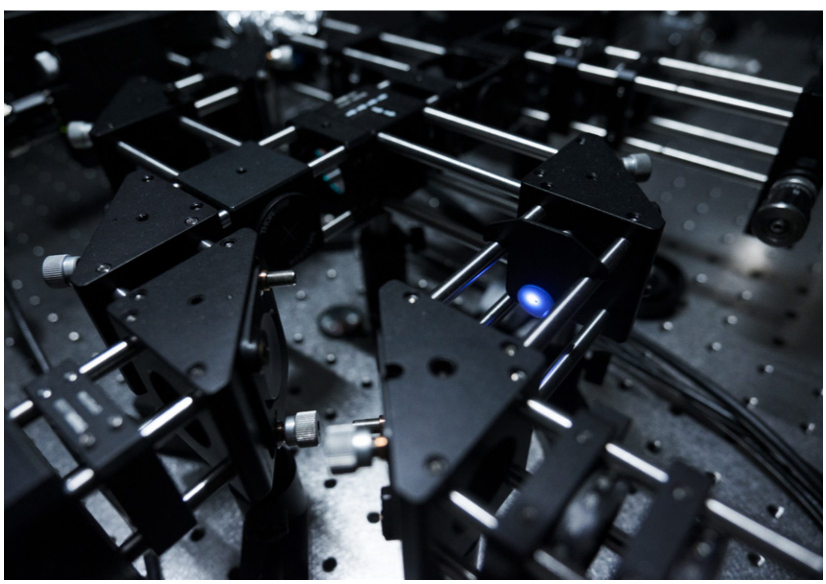
In collaboration with Professor Liu Zheng from NTU Singapore's School of Materials Science & Engineering, our team conducted experiments to check this. We used $NbOCl_2$ flakes with a combined thickness of 1.2 μm, or about 80x thinner than a strand of hair.

Results of our experiments support Gao's hypothesis, and the photon pairs produced show an 86% resemblance to ideally entangled photons. This suggests our method

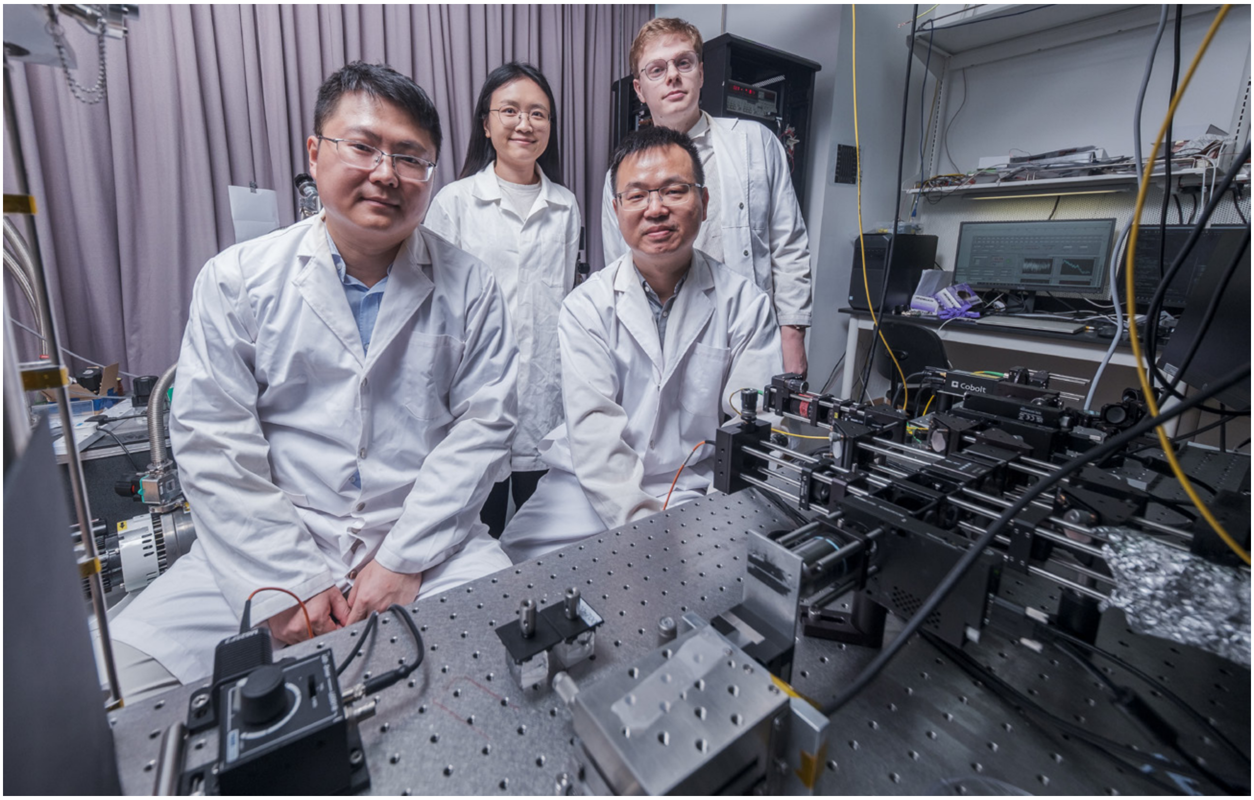
> Novel method may enable more compact, scalable, and efficient quantum systems.

is a reliable way for producing qubits for quantum computing.

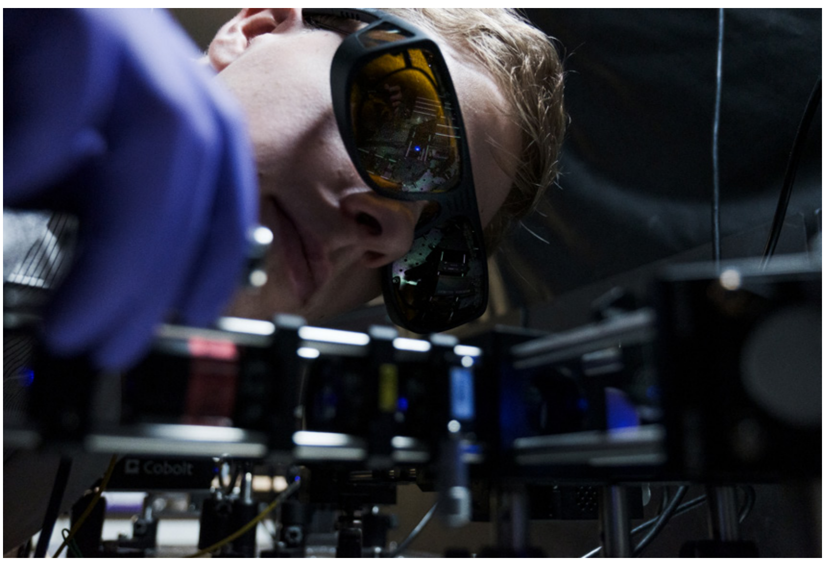
The novel method "is a major advancement, potentially enabling the miniaturization and integration



A closeup of the blue laser setup for generating entangled photon pairs in NTU Singapore's experiments. (Image credit: NTU Singapore)



(L-R) Professor Weibo Gao, Dr. Xiaodan Lyu, Professor Liu Zheng, and Ph.D. student Leevi Kallioniemi are part of the NTU Singapore team that found a new way to produce entangled photon pairs with very thin materials. (Photo credit: NTU Singapore)



Ph.D. student Leevi Kallioniemi from NTU Singapore's School of Physical & Mathematical Sciences with a blue laser setup for generating entangled photon pairs. (Image credit: NTU Singapore)

of quantum technologies," says Professor Zhipei Sun from Finland's Aalto University, who specializes in photonics and was not involved in NTU Singapore's research. Sun is a co-principal investigator at the Research Council of Finland's Center of Excellence in Quantum Technology.

"This development has potential to advance quantum computing and secure communication, because it allows for more compact, scalable, and efficient quantum systems," he adds.

We are now planning to optimize our setup to improve its photon generation output, which will involve studying whether introducing tiny patterns and grooves on the $NbOCl_2$ flakes' surface could boost the creation of linked photon pairs. We are also exploring whether photon production can be improved by stacking other materials with the $NbOCl_2$ flakes.

FURTHER READING

L. Kallioniemi et al., *Nat. Photon.* (Oct. 2024); https://doi.org/10.1038/s41566-024-01545-5.

Leevi Kallioniemi is a Ph.D. student and **Xiaodan Lyu** is a research fellow, both at Nanyang Technological University, Singapore; e-mail: leeviale001@e.ntu.edu.sg; www.ntu.edu.sg.

Novel quasicrystal design further 'green lights' topological study of light

A new quasicrystal design process—that enabled a structure with a 12-fold rotational symmetry—may prove useful for many photonic applications beyond plasmonics.

SALLY COLE JOHNSON, EDITOR IN CHIEF

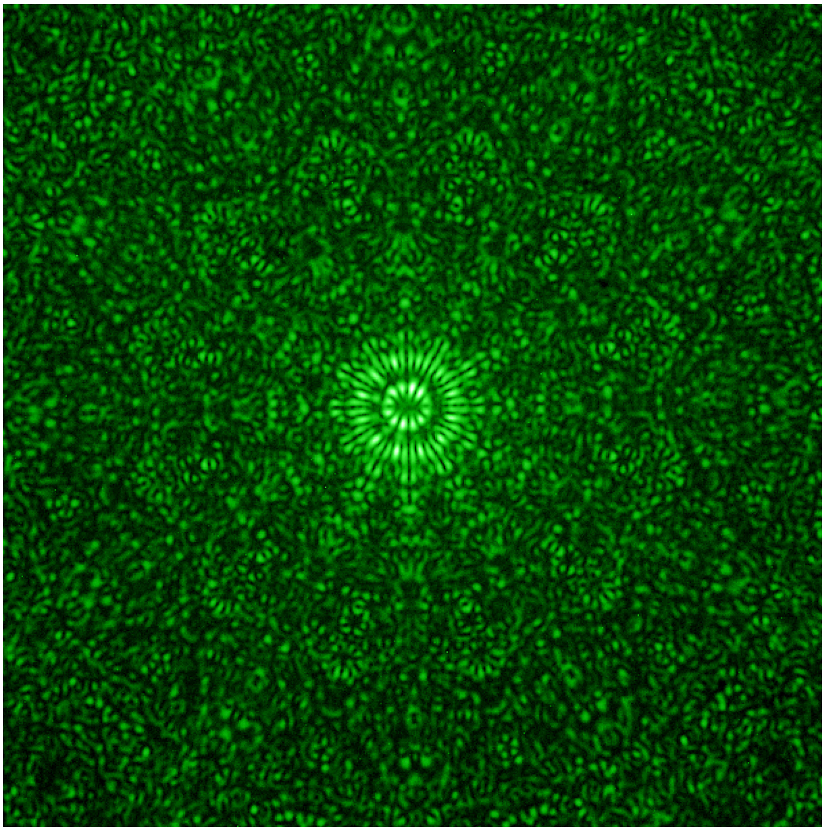
Aalto University researchers in Finland believe a novel quasicrystal-based method they developed to create light vortices may one day enable an entirely new way to encode and transport large amounts of data.

Professor Päivi Törmä's Quantum Dynamics group explores metallic nanoparticles that interact with an electromagnetic field (plasmonics). The theoretical framework for the quasicrystal design method was developed by Kristian Arjas, a doctoral researcher, and was experimentally achieved by Jani Taskinen, who was finishing his Ph.D.

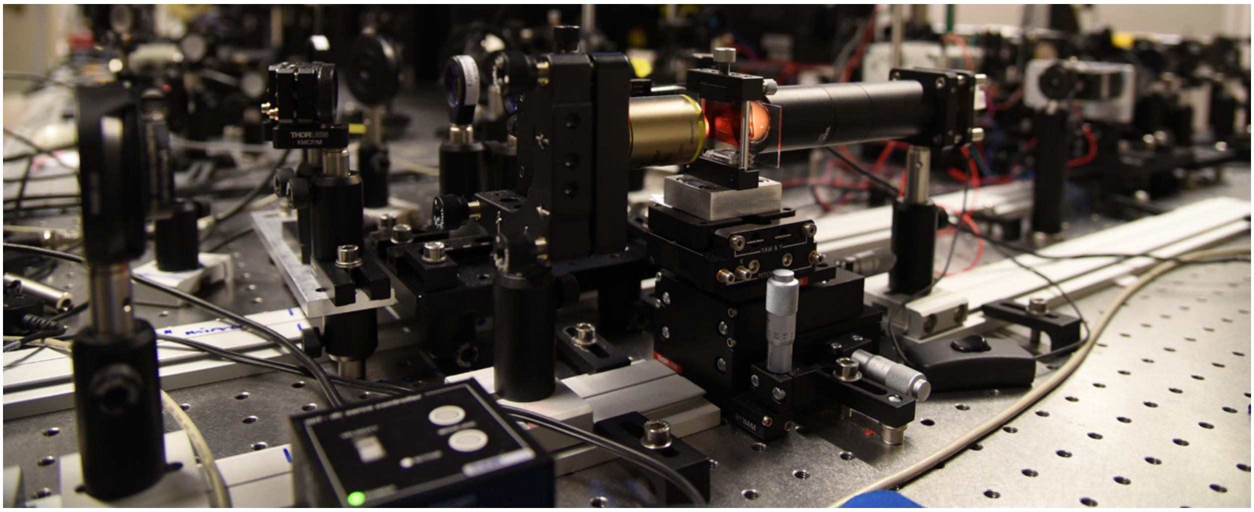
The group's work was inspired by an earlier study of theirs, in which they found they could select a specific vortex for lasing within periodic structures by placing nanoparticles in specific positions. But only a few different vortices were available due to the geometric constraints—and getting more vortices meant moving into the realm of quasicrystals (aperiodic, but ordered structures) where higher rotational symmetries exist.

"Like many great ideas, the quasicrystal structures were originally an attempt to solve an entirely different problem related to magnetic materials. While this project never came to fruition, Arjas's creativity allowed us to leverage tools learned along the way to generate these unprecedented plasmonic devices," says Taskinen.

Lasing within plasmonic nanoparticle lattices isn't new. "Such devices represent one form of distributed-feedback lasers where a periodic structure supports a standing wave,"



Vortex laser pattern from 12-fold rotationally symmetric quasicrystal structure. (Image credit: K. Arjas et al., Nat. Commun., 15, 9544 [2024]; https://doi.org/10.1038/s41467-024-53952-5)



The group's lab setup. (Image credit: Konstantinos Daskalaskis)

says Taskinen. "These modes can then be amplified by adding a gain material and external pumping. For our work, we combine two-dimensional (2D) devices with dye molecules and pump them optically with another laser. The amplified waves are plasmonic excitations—quasiparticles composed of electromagnetic waves and electron oscillations on the surface of the nanoparticles."

The tricky part is designing the lattice geometry so plasmonic modes generate laser beams with polarization vortices, and this is where the group's novel quasicrystal design process becomes crucial.

"We can tell which vortices are present from the sample's symmetry," says Arjas. "Quasicrystals give us more options (and more complex vortices) due to their higher degree of rotational symmetry. But it comes at the cost of long-range order, which is a necessity for providing a strong enough feedback mechanism for plasmonic lasing. The problem becomes two-fold: how to select a specific mode from many modes with similar energies and how to make it lase."

Symmetry "is one of the few things nature must respect," Arjas points out. And it just so happens to be what allowed the researchers to connect different theoretical models to each another and to experiments.

"Our quasicrystal design process can be useful for many other photonic applications beyond plasmonics," says Taskinen. "The mode selection was driven by spatially applied plasmonic losses, but nothing prohibits the use of localized gain structures to achieve a similar result. It goes to show sometimes losses within an optical system can be useful."

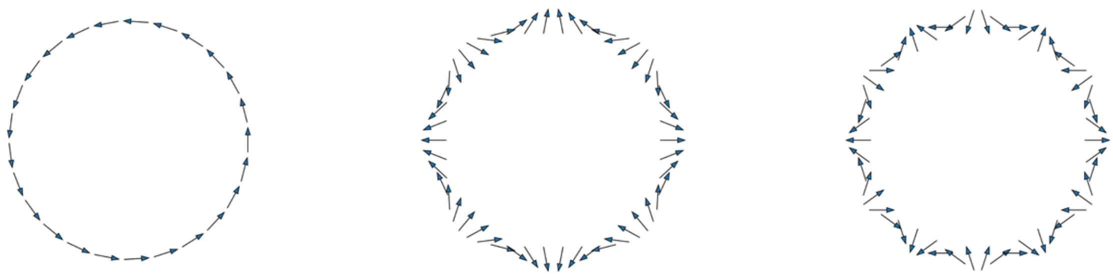
Design process

From a theoretical standpoint, the group's design process consisted of three steps: Identifying dead spots within the electric field and placing particles there; introducing long-range order within the system to enable standing waves, which is a necessity for plasmonic lasing; and, finally, adding finishing touches to make the sample as uniform as possible to avoid any unwanted effects.

"The design was done in quick iterative cycles in close collaboration with Taskinen, so I could make a set of initial theory-based designs that he would finalize based on his experience with plasmonic systems," says Arjas. "He then fabricated and measured the structures and gave me the data, which I used to refine the theoretical model for the next iteration. We went through this cycle about eight times."

Plasmonic structures are "inherently lossy and, while this property allows us to implement the quasicrystal design process, it hinders the quality of the lasing modes," explains Taskinen. "Experimentally, the work was very much a balancing act between two principles: having enough nanoparticles in the quasicrystal to enforce mode selectivity while keeping the overall losses small enough to support lasing."

In the end, many of the correct quasicrystal parameters could be found only by trial and error, which involved multiple rounds of sample fabrication within cleanroom conditions and lasing measurements within the optics lab. "To explore the optical properties of these devices, we pumped the samples with ultrafast laser pulses and analyzed the emission with an angle-resolved spectrometer setup," says Taskinen.



Visualization of the polarization vortex, which shows the electrical field polarization around the beam center corresponding to topological charges +1 (left), -3 (center), and -5 (right). (Image credit: Kristian Arjas)

Challenges and a surprise

From a theoretical perspective, the group's primary challenge was figuring out how to model the structure.

"For periodic structures, it's enough to do the calculations for the part that repeats and then go from there," says Arjas. "But the lack of periodicity within our structure threw this approach out the window and we had to find a way to model the entire structure simultaneously. This, combined with the fact that plasmonic lasing typically requires roughly 100,000 interacting particles within a single sample, put computational complexity with standard methods far beyond our reach."

They sidestepped the problem by simply ignoring particle-particle interactions. Metallic particles within an oscillating electric field act as dampeners because part of the energy gets transformed into heat. After figuring this out, it was simple for the team to find a good approximation of the field seen by the nanoparticles corresponding to the desired vortex. Then, they placed particles where the field showed the least activity (the smallest losses).

"The parameter space of plasmonic lasers sometimes seems overwhelming, so we need a certain 'feel' to the experiments to see the correlations between different lattice designs, adjustments to the optical setup, and the resulting emission properties," says Taskinen. "At some point, the measurements tend to become an optimization problem to solve in a pitch-black optics lab with a screwdriver, which can be surprisingly fun."

After they managed to get the method working for vortices in 8- and 10-fold rotationally symmetric structures, Arjas decided to generate a structure with a 12-fold rotational symmetry (because why not!). Taskinen prepared the sample and measured its lasing properties successfully on the first try, and they were both awestruck when the data showed far more intricate behavior than they'd expected—multiple different vortices and clear transitions between them. As far as they're aware, this was the first time anything like it was observed within a beam of light—particularly a beam of laser light generated from a single structure.

Advance for telecom

The most obvious application ahead for the team's discovery is telecommunications.

"Information is encoded into pulses of light in what physicists call degrees of freedom," says Arjas. "These are different aspects of light you can manipulate, such as wavelength (color), phase, polarization, or brightness, to name a few. The more of these you can encode into a single packet, the more information you can send via a single pulse. These vortices could provide an additional piece of information sent with each package, and the amount of extra information depends on how many different vortices can be included."

The group's vortices can potentially be sent down fiber-optic cables and unpacked at their destination. It would enable storing information in a much smaller space and transmitting much more of it at once. How much more? Perhaps 8 to 16x the amount we can currently deliver via fiber-optic cables.

And since the team's pioneering work is a general design method for 2D optical devices, "it can be applied to a plethora of systems within the field of photonics," Taskinen adds.

Next up, Arjas is pursuing more exotic topological phenomena on these plasmonic lattices during the remainder of his Ph.D. studies with Professor Törmä.

This work was the finale of Taskinen's Ph.D. studies and, although he's moved on to an entirely different topic, the Quantum Dynamics research team continues to explore plasmonic devices. Beyond topological effects, the team has begun exploring plasmonic applications—focusing on improving the efficiency of organic light-emitting diodes using metallic nanostructures—and topological features may also prove to be useful for this endeavor.

FURTHER READING

K. Arjas et al., *Nat. Commun.*, 15, 9544 (2024); https://doi.org/10.1038/s41467-024-53952-5.

Tabletop optical alignment: A nightmare for QED scientists (with a solution)

Precision optical alignment is currently used for centering lenses within cells, but a call from a quantum computing company made us realize it would be more helpful to quantum electrodynamics (QED) researchers than conventional optics users because, on a tabletop, they have all the degrees of freedom needed to perfectly align their optics.

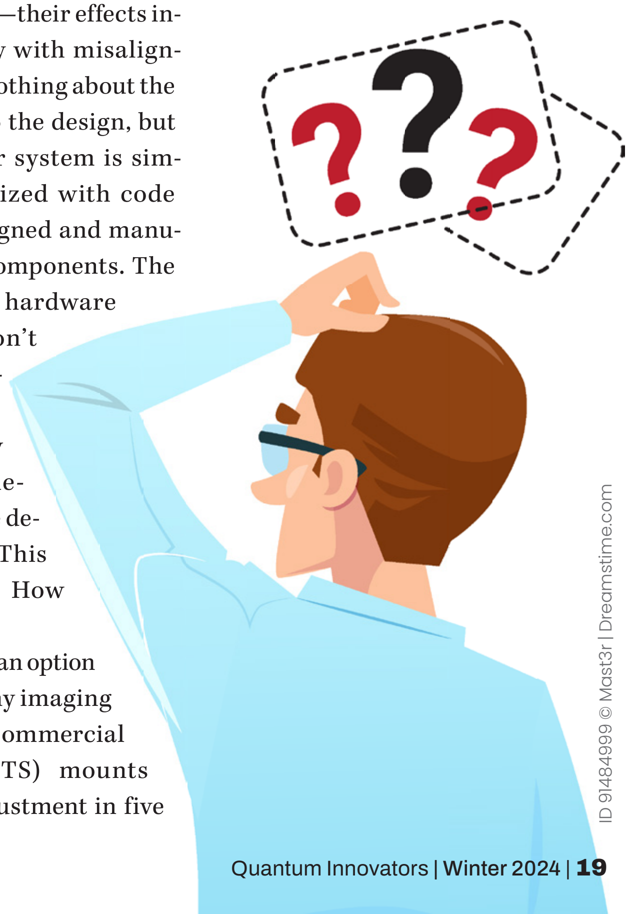
ROBERT E. PARKS

A quantum computing company reached out with a tabletop optical alignment nightmare situation, so we loaned them an autostigmatic microscope to demo. Although they had no experience using our Point Source Microscope, within a week, they had achieved their best performance to date.

At first glance, the alignment of tabletop optical elements may seem straightforward: follow the laser beam path with a card and center lenses on the beam. But the alignment requirements are as tight or tighter for more complex systems, such as those used in quantum computing, than for imaging optics. A new method promises to transform this process—by allowing for the alignment of tabletop optics to <1 µm of decenter and <5 microradians of tilt using a Bessel beam as the reference axis.

Why are the requirements tighter? Aberrations to laser beam quality are not linear with numerical aperture (NA) and field of view (FOV), but increase as their square and higher powers. The same goes for aberrations introduced by lens decenters and tilts—their effects increase nonlinearly with misalignment. You can do nothing about the aberrations due to the design, but the design of your system is simulated and optimized with code using perfectly aligned and manufactured optical components. The designed system's hardware performance won't achieve the design performance without flawlessly aligning each element in at least five degrees of freedom. This is the nightmare: How do you do it?

Luckily, you have an option unavailable in many imaging optical systems: Commercial off-the-shelf (COTS) mounts that allow fine adjustment in five degrees of freedom. Theoretically, each lens's optical axis can be made coaxial with a reference axis, and lens spacings can be adjusted. In addition, you can use a Bessel beam as a reference axis because it propagates through an optical system like a single ray in a lens design program.[1] The Bessel beam and a reflection from the center of curvature of one of the lens's surfaces provide the two points used for feedback to adjust the lens's optical axis so it is coaxial with the reference axis.[2]



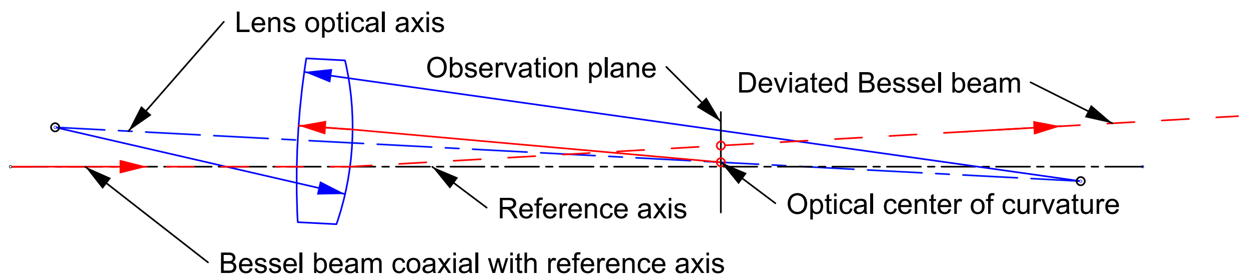


FIGURE 1. A misaligned lens inserted into a Bessel beam pre-aligned to an ASM.

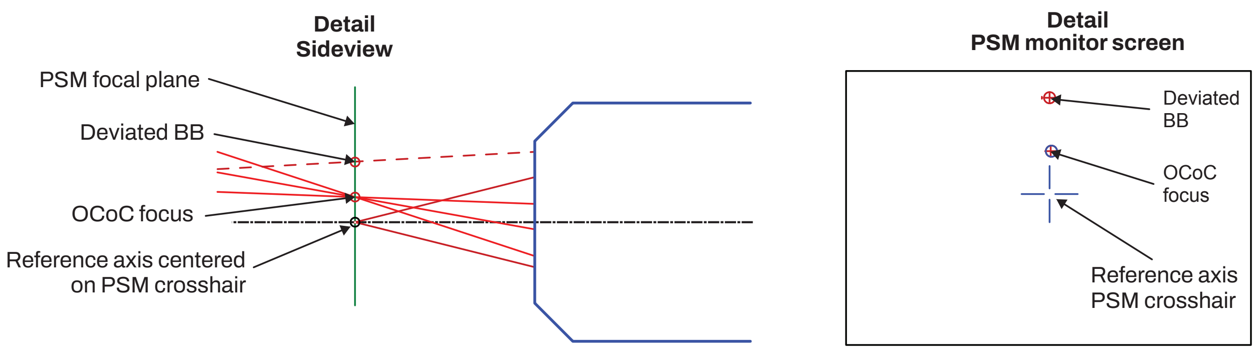


FIGURE 2. A detail side view of the ASM focal plane (left) and a view on the ASM monitor (right).

Alignment

The alignment process involves an autostigmatic microscope (ASM) or autocollimator with a microscope objective. It is used to view the Bessel beam, illuminate the lens's spherical surface from its optical center of curvature, and view the reflected image. The lens's optical axis is coaxial with the reference axis when the two spots are centered on the crosshairs in the ASM pre-aligned to the pinhole light source. Figure 1 shows a lens inserted into a Bessel beam after the ASM was centered on the beam. Neither the Bessel beam nor the optical center of curvature now lie on the axis of the original beam due to the misalignment.

Figure 2a is a detail of the focal plane where the ASM views the two spots, while Figure 2b shows the spots and crosshair as viewed on a monitor or through an eyepiece.

In an easy and quickly converging iterative procedure, the lens is decentered to bring the Bessel beam onto the crosshair. Then, the lens is tilted to bring the optical center of curvature onto the crosshair. This step slightly decenters the Bessel beam, so the lens must be recentered and then tilted. The process usually takes 3 to 4 iterations to bring the alignment to <1 μm and <5 microradians tilt from a condition where both light spots are aligned well enough to enter the microscope objective (see Fig. 3). The figures show the alignment process in two dimensions, but it works for all three dimensions.

Since the Bessel beam used as the reference axis is again coaxial with the initial beam after exiting the aligned lens to small tolerances, the beam is used to align the next lens in the chain. The same procedure is used lens after lens until the system focuses on the target.

Convergence

Convergence is iterative as a practical matter. If the lens could be rotated about the point where the optical axis crosses the reference axis, just to the right of the optical center of curvature in Figure 1, the alignment could be accomplished in one step. Almost all adjustable lens mounts tilt the lens about a pivot close to the lens, and tilt about this point decenters the Bessel beam slightly so further correction is needed. But this is a simple task since the two light spots are continuously visible on the monitor, and the process converges rapidly (see Fig. 4).

Figure 4a shows the simulated, iterative alignment convergence using lens design code to drive the Bessel beam ray height or center of curvature to zero. Figure 4b shows the iterative convergence for an experimental alignment result for a similar but not identical lens used in the

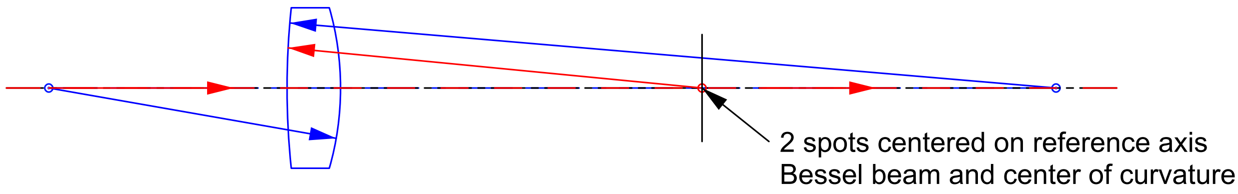


FIGURE 3. The lens is fully aligned with the reference beam, which makes the transmitted beam coaxial with the beam entering the lens and the reference axis.

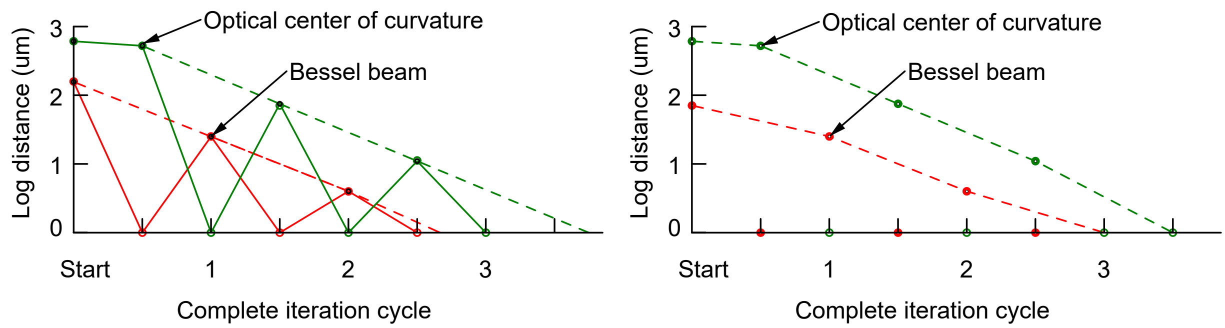


FIGURE 4. Simulated convergence of alignment (a) and experimental convergence of alignment (b).

simulation. The distance from the reference axis is on a log scale in the graphs because a linear scale would not show the details of how the alignment converges at a typical factor of 3 to 4x each cycle. Also, negative distances were treated as positive. Zero makes no sense on a log scale, but it is intended to represent the ASM's resolution limits.

The figure also shows how the Bessel beam alignment slightly misaligns with the center of curvature alignment in the first half of the alignment cycle, and then tilting the lens misaligns the Bessel beam. Also, the sensitivity of the Bessel beam to tilt is less than the sensitivity of the center of curvature for the positive lens used as an example. And it is helpful to know that for any lens and pivot point, it is possible to simulate the improvement in alignment before doing the alignment in the lab so potential alignment problems are known in advance.

It is clear from Figure 4a that it is possible to go from a substantial misalignment in tilt and decenter to full alignment to the limits of resolution of a suitable detector in 3 to 4 iterative alignment cycles using continuously available data on the degree of misalignment. This means it is possible to align a lens within less than a minute to <1 μm in decenter and <1 second of arc, given a practical radius of curvature used for centering.

Using an autostigmatic microscope, lens mounts with 5 degrees of freedom, and a Bessel beam as a reference axis, it is possible to achieve alignment precision comparable to or better than using a rotary axis as a reference. If the right tools are used, the tabletop optical alignment nightmare for QED researchers is over.

REFERENCES

1. M. Santarsiero, *Opt. Commun.*, 132, 1–2, 1–7 (1996).
2. R. E. Parks and R. Greenberg, *Proc. SPIE*, 13133, 1313303 (Sep. 2024); https://doi.org/10.1117/12.3027687.

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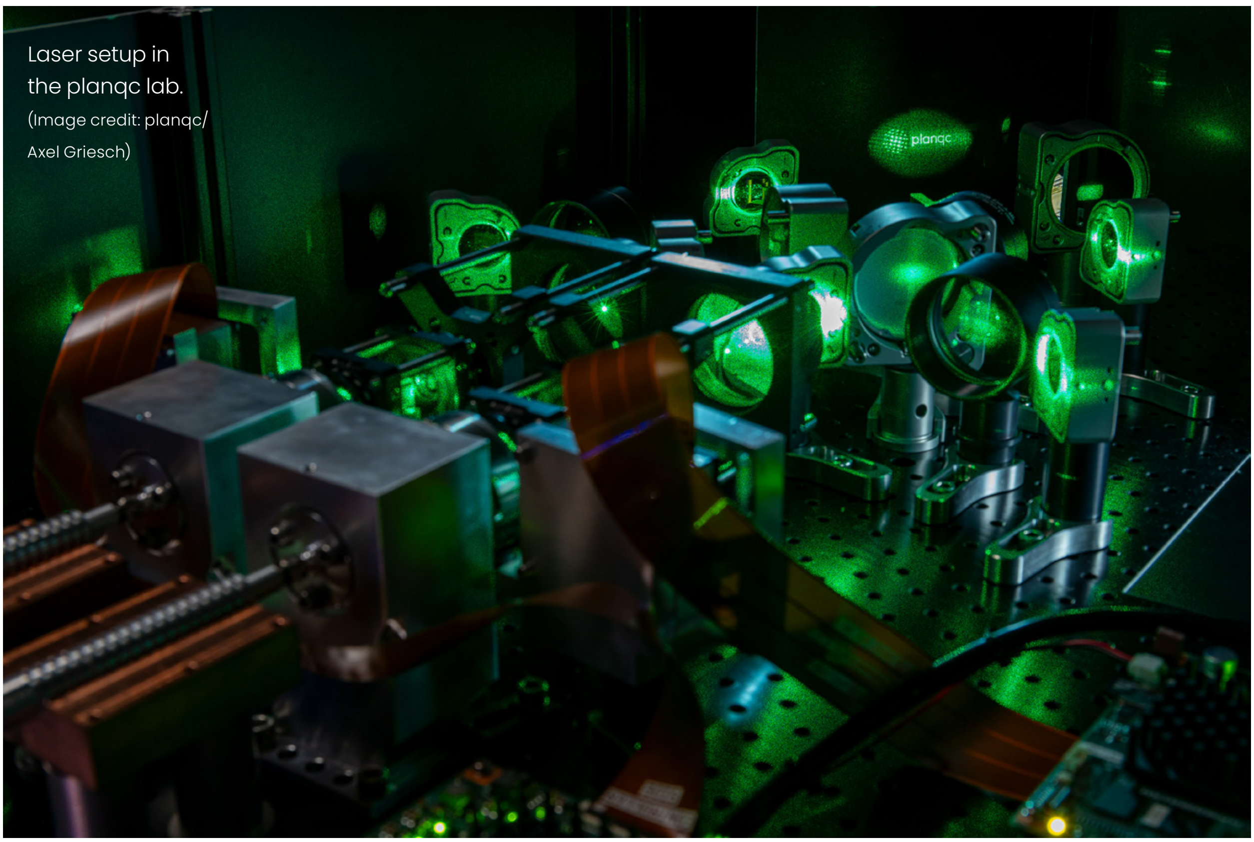
Continuously operated quantum registers with neutral atoms

A qubit register of 1,200 neutral atoms within an optical lattice of laser light designed to 'reload itself' was kept in continuous operation for an hour—progress toward scaling up quantum computing platforms.

JOHANNES ZEIHER

Systems of many interacting quantum particles feature a remarkably rich phenomenology due to the complex interplay between their constituents. Examples include the collective behavior found in low-dimensional quantum magnets or the emergence of exotic superfluids. To understand such phenomena, physical sciences resort to classical simulations of their underlying models. While these classical simulations made big strides explaining various phenomena, for very complex systems, often with dynamics, classical calculations are doomed to fail and exceed the capabilities of today's most advanced supercomputers. This failure of classical methods to accurately simulate some quantum mechanical systems is due to the exponential scaling of complexity with system size.

At the same time, a fundamental understanding of complex quantum systems is essential for predicting the properties of, for example, certain materials or biomolecules. In the early 1980s, physicist and Nobel



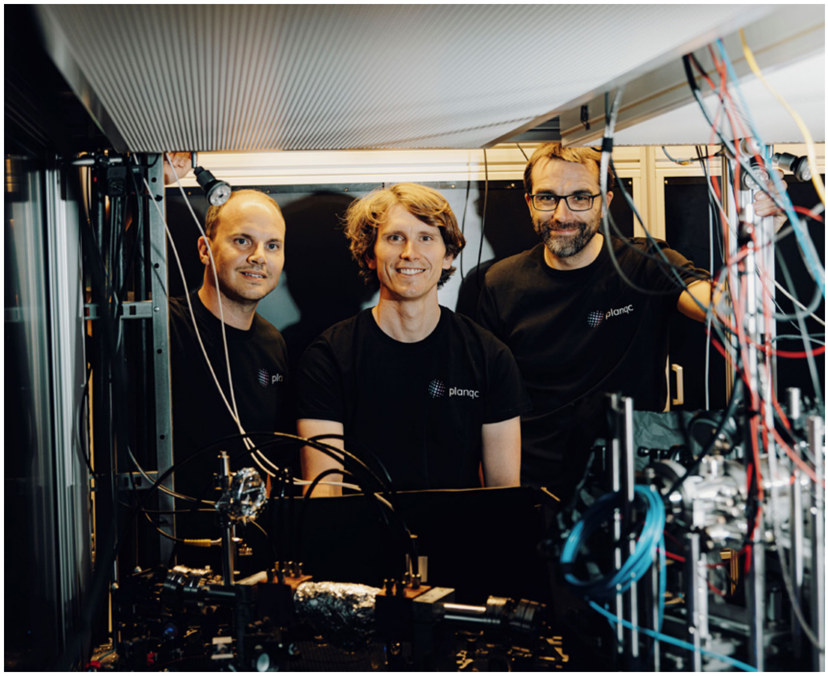
Laser setup in the planqc lab. (Image credit: planqc/ Axel Griesch)

Prize laureate Richard Feynman proposed using quantum simulators and computers to calculate complex quantum mechanical phenomena rather than classical computers because they obey the same laws as the systems to be calculated and circumvent the limitations of classical computers.

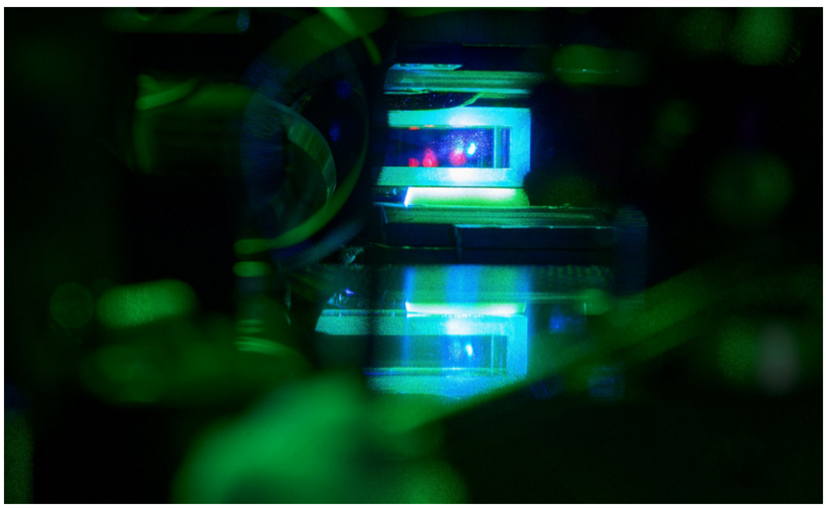
While quantum simulators are primarily suited to specific, platform-tailored problems, such as in solid-state physics or elementary quantum magnets, digital quantum computers are more universally applicable.

But their additional capabilities come at the cost of increased complexity: creating digital quantum computers requires individually controllable qubits, which are the elementary units for storing and processing quantum data. Interactions between such qubits can be exploited to achieve entanglement, which, together with the superposition of different qubit states, form the basis of the alleged computational power of quantum computers.

The wide range of applications for quantum computers opens up new scientific and technological possibilities, for example, when quantum computers are tightly integrated with classical supercomputers to perform certain, specifically portioned and tailored subtasks more efficiently than their classical counterparts.



Founders of neutral-atom quantum computing startup planqc: Alexander Glätzle, Johannes Zeiher, and Sebastian Blatt. (Image credit: planqc/Dirk Bruniecki)



Glass cell with a cloud of laser-cooled strontium atoms hovering above a high-resolution microscope objective in our experiment at the Max Planck Institute of Quantum Optics. (Image credit: Max Planck Institute of Quantum Optics/Munich Quantum Valley)

Scalability and error correction

A major hurdle to create quantum computers powerful enough to meet these expectations is the scalability of the number of qubits while maintaining single-qubit control. These challenges must be overcome to achieve quantum error correction, which is generally accepted as a prerequisite for building a digital quantum computer.

Neutral atoms confined within individual optical traps are one of several competing approaches to achieving error-corrected quantum computers. In this platform, the qubits are encoded within the internal states of individual atoms. Such an approach to quantum computing is advantageous because individual atoms have no production variability, unlike platforms where qubits are encoded within solid-state systems.

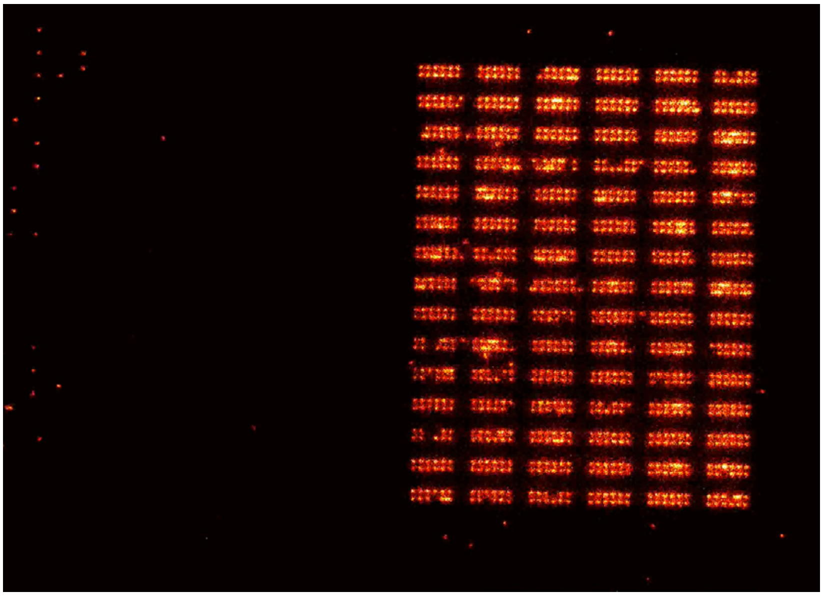
While scalable trapping is possible using optical lattices, which can be thought of as light crystals formed by interfering laser beams, qubit control can be obtained by adding tightly focused laser beams. Together with the ability to read out the state of individual qubits, the platform fulfills all elementary requirements for achieving so-called fault-tolerant quantum computers based on error-corrected logical qubits.

One critical step in the pursuit of error-corrected neutral atom quantum computers is the ability to run neutral atom experiments continuously. Traditionally, neutral-atom experiments are operated in a mode where the atomic register is cleared after one run and the entire register is reloaded for every new run. Such a mode of operation would be incompatible with scalable error-corrected qubits that may need to run for extended periods of time to tackle some of the applications mentioned above. Therefore, continuous operation is paramount to unlock the potential of quantum computers and simulators based on neutral atoms.

Recycling atoms to create larger-scale registers

In our experiment at the Max Planck Institute of Quantum Optics and in collaboration with the neutral-atom quantum computing startup planqc, our group recently succeeded in maintaining an atomic register in continuous operation. The key to this breakthrough was combining two special trapping regions and the specific internal-level structure of the alkaline earth atom strontium, the species of choice in our experiment.

Using an optical lattice as the storage register and an optical tweezer array as the loading register, we added 130 fresh atoms to the storage register in a cycle—replacing lost atoms in the storage zone.



A neutral atom qubit register, which continuously reloads new atoms into the register. (Image credit: Max Planck Institute of Quantum Optics)

To enable the reloading, the atoms already present in the storage register were transferred to a metastable triplet state, typically found in alkaline earth and alkaline-earth-like atoms, which enables reloading without significant effect on the atoms already present in the register. Moreover, the ability to retain and reuse existing atoms in the register enables an iterative assembly of larger registers than would be possible otherwise.

The register achieved with this technique reached a size of about 1,200 atoms—nearly an order of magnitude more than the number of atoms loaded in a single cycle. Such a scaling advantage can be directly translated into advantages in applications such as quantum simulation, where larger-scale systems with microscopic control have advantages in terms of reducing the artificial effects in the system due to the boundaries, or in quantum metrology, where the number of atoms in a system translates into the achievable precision with which certain quantities can be measured—for example, frequencies in an atomic clock.

The next steps in this experiment are to control the internal electronic state of the atoms, for example, using optical tweezers, so that each individual atom in the array becomes a qubit holding quantum information. Adding controlled interactions between nearby atoms in the array then enables the generation of quantum entanglement—the basis for any quantum computation and a subject of ongoing research in quantum many-body systems, where it is thought to play an important role in unlocking some of the secrets of complex quantum matter.

FURTHER READING

F. Gyger et al., *Phys. Rev. Res.*, 6, 033104 (Jul. 25, 2024); https://doi.org/10.1103/physrevresearch.6.033104.

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Quantum key distribution: Secure optical communications

Avalanche photodiodes, infrared sensors capable of detecting single photons, are at the heart of many QKD systems. Their sensitivity allows them to discern the faintest of light signals down to an individual photon.

YE CAO

In the ever-evolving landscape of cybersecurity, quantum key distribution (QKD) promises unbreakable encryption for optical communications. This cutting-edge technology harnesses the enigmatic principles of quantum mechanics to create a fortress around our most sensitive data. As we delve into the world of QKD, we'll explore its purpose, inner workings, and the crucial role of infrared sensors for the quantum revolution.

Role of cryptographic keys

Cryptographic keys—typically strings of random numbers and letters—play a pivotal role in modern information security (see Fig. 1). They enable secure data exchange in various contexts, including cryptographic infrastructures, data center security, and the protection of sensitive information for sectors like healthcare and finance. Crypto keys are crucial for safeguarding critical infrastructure systems such as smart grids and national defense communications. Beyond this, advanced key distribution methods facilitate long-distance secure communication, with innovations paving the way for global secure networks.

Specialized applications are emerging for diverse fields, from securing genome data transmission to protecting high-value intellectual property for industries like aerospace and pharmaceuticals. Research and development efforts are also adapting key distribution techniques for mobile and dynamic networks to enhance communication security for scenarios such as

FIGURE 1. Cryptographic keys ensure controlled access to communication channels. *(Image credit: Phlux Technology)*

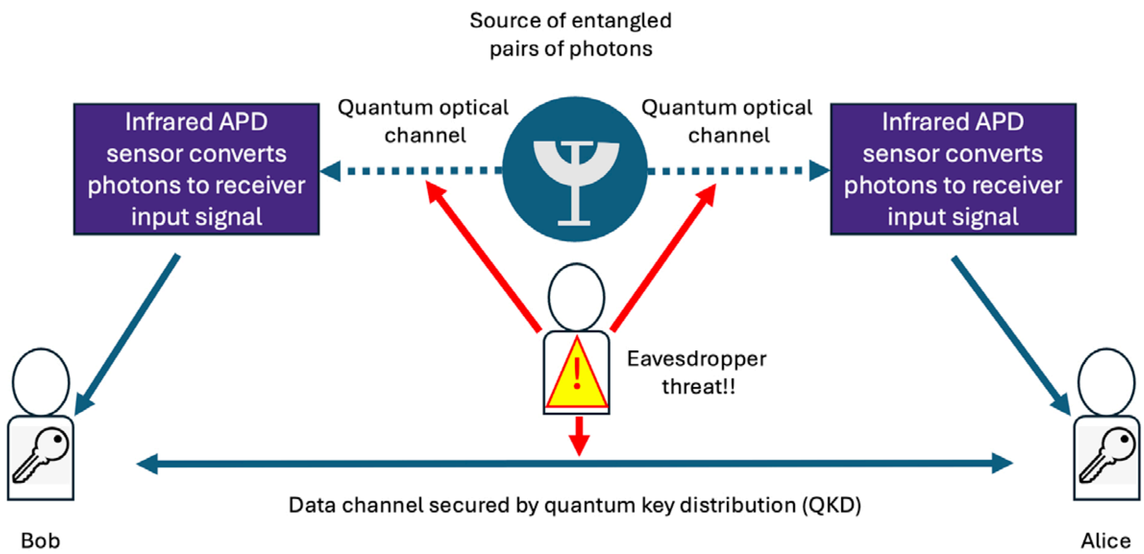


FIGURE 2. Two-channel communication link protected by quantum key distribution. *(Image credit: Phlux Technology)*

ship-to-ship interactions and autonomous vehicle coordination. While some organizations have reservations about certain key distribution methods for national security applications, ongoing advancements aim to address these challenges.

Quantum advantage

At its core, QKD addresses a fundamental vulnerability of traditional cryptography: the key exchange process. As computational power surges forward and the specter of quantum computers looms on the horizon, conventional methods of key distribution are increasingly at risk. QKD offers a paradigm shift by basing its security not on mathematical complexity, but on the immutable laws of physics.

The beauty of QKD is its elegant simplicity. Individual photons, the fundamental particles of light, are encoded with quantum states representing bits of a cryptographic key. These photons are then transmitted over an optical fiber link to create a secure channel between two parties. The quantum nature of these photons ensures that any attempt to intercept or measure them inevitably disturbs their delicate state—immediately alerting the communicating parties to the presence of an eavesdropper.

Infrared sensors: The eyes of quantum communication

Within the realm of QKD, infrared (IR) sensors serve as the vigilant sentinels—ever watchful for the arrival of these quantum messengers. Most QKD systems operate within the IR spectrum, typically at wavelengths around 1550 nm, which align with the low-loss windows of optical fibers (see Fig. 2).

The sensitivity of these IR sensors is paramount and directly impacts the performance and capabilities of QKD systems. High sensitivity allows for the detection of weaker signals, which is a crucial factor because of the inherently faint nature of quantum signals. This enhanced

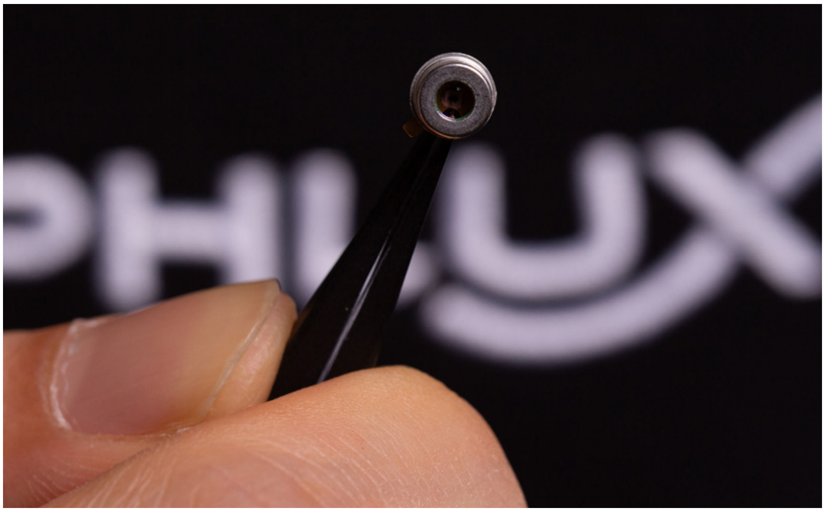


FIGURE 3. Noiseless indium gallium arsenide (InGaAs) APD infrared sensors can extend the range, performance, and reliability of optical networks used for quantum key distribution. *(Image credit: Phlux Technology)*

sensitivity translates into tangible benefits: increased maximum transmission distances, higher key generation rates, and improved tolerance to channel losses and noise.

As researchers push the boundaries of IR sensor technology, the horizons of QKD expand and bring us closer to a world where quantum-secure communication is the norm rather than the exception.

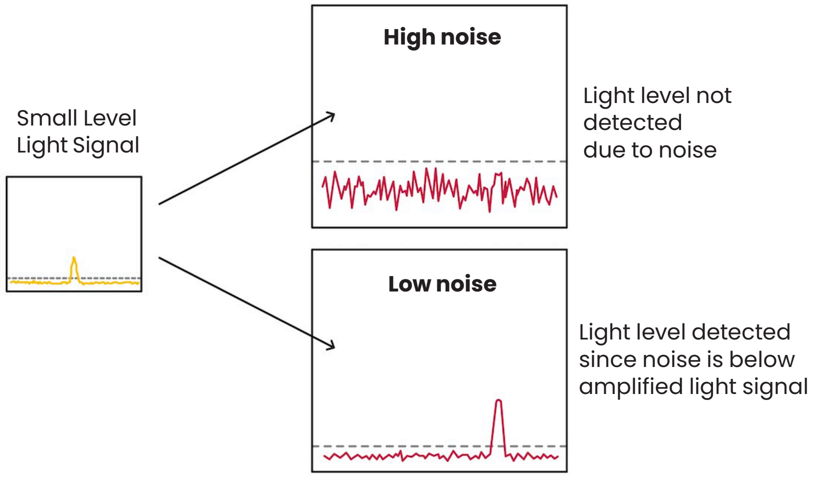


FIGURE 4. Lower noise results in 12x better infrared detector sensitivity for QKD applications. *(Image credit: Phlux Technology)*

Avalanche photodiodes: Amplifying the quantum whisper

Avalanche photodiodes (APDs), IR sensors capable of detecting single photons, are at the heart of many QKD systems. These devices operate on the principle of the avalanche effect, where a lone incident photon triggers a cascade of electron-hole pairs and amplifies the signal to a measurable current.

The choice of APDs for QKD is no coincidence. Their sensitivity allows them to discern the faintest of light signals down to an individual photon. This is coupled with rapid response times, which enables the high-speed key generation crucial for practical applications. Moreover, when properly cooled, APDs exhibit impressively low noise levels and maintain the low error rates essential for reliable quantum communication.

Advancing QKD with improved APD technology

Recent advancements in APD technology have the potential to significantly enhance QKD systems. For instance, the Phlux Aura APD, based on noiseless indium gallium arsenide (InGaAs) technology (see Fig. 3), offers improved performance over traditional InGaAs APDs. These sensors provide as much as 12x higher sensitivity and can operate with APD gains up to 120, which enables detection of even the smallest signals above the noise floor (see Fig. 4).

For QKD applications, this enhanced sensitivity could translate to several benefits. The increased detection efficiency allows for longer transmission distances and potentially extends the range of QKD networks. Higher sensitivity also means that weaker quantum signals can be reliably detected, which could lead to improved key generation rates and better tolerance to channel losses. And the ability to operate at higher temperatures without performance degradation could simplify the thermal management requirements of QKD systems.

QKD use case: The Marconi project

As we stand on the cusp of a quantum communication revolution, initiatives like Innovate U.K.'s Marconi project are leading the charge in translating theoretical promise into practical reality. Named after the visionary radio engineer Guglielmo Marconi, the Marconi project is a collaborative research initiative aimed at advancing quantum communication technologies, particularly in the realm of satellite-based quantum key distribution.

The Marconi project brings together experts from academia, industry, and government agencies to tackle the challenges of implementing QKD on a global scale. The project's goals include developing more efficient QKD protocols, creating robust quantum communication satellites, and establishing international standards for quantum-safe cryptography.

As the Marconi project and others like it continue to push the boundaries of what's possible, we edge closer to a future where quantum-secured communications are not just a possibility but a ubiquitous reality. In this quantum-safe future, our most sensitive data will be protected by the fundamental laws of nature and usher in a new era of information security in our increasingly connected world.

Ye Cao is an application engineer at Phlux Technology, a manufacturer of high-sensitivity avalanche photodiodes for infrared sensing applications based in Sheffield, U.K. He earned a Ph.D. from the University of Sheffield in infrared avalanche photodiodes.

Bright squeezed vacuum pulses generate high harmonics

Using a bright squeezed vacuum to generate high harmonics enhances their yields—compared to classical coherent light—and provides a route to probe material properties beyond the damage threshold.

SALLY COLE JOHNSON, EDITOR IN CHIEF

Max Planck Institute for the Science of Light (Germany) researchers led by Maria Chekhova, whose group focuses on quantum radiation, and Francesco Tani, whose group explores ultrafast and twisted photonics, in collaboration with Denis Seletskiy from Polytechnique Montreal (Canada) and researchers from Technion (Israel), recently combined forces to explore generating high harmonics via different kinds of light (noncoherent photon statistics).

Based on their previous work, they anticipated new and interesting observations and expected pulses of bright quantum light, a.k.a. "bright squeezed vacuum," could be a good way to enhance multiphoton effects.

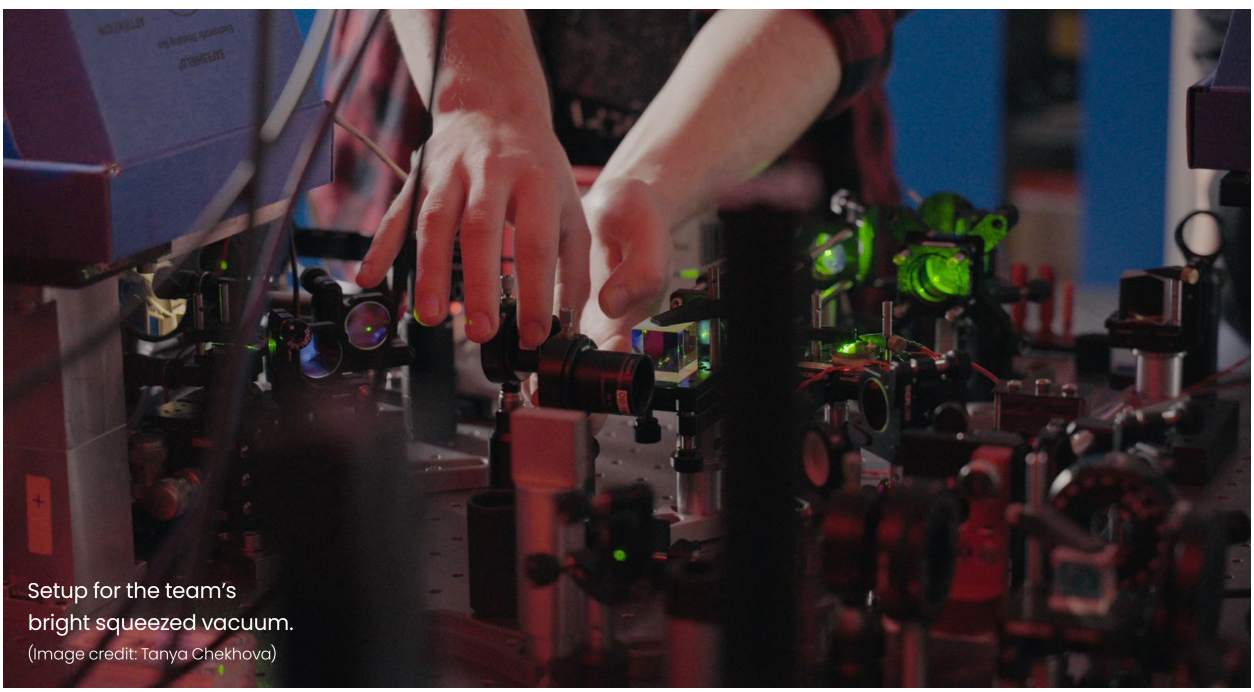
Inspiration

In 2023, colleagues at Technion reported theoretical work to generate nonperturbative high harmonics within gaseous media—the main route to generate coherent pulses within the extreme ultraviolet and x-ray spectral regions with durations as short as a few tens of attoseconds—by quantum light and predicted the spectral coverage of high-harmonics sources can be significantly extended.[1]

"Other researchers simultaneously started exploring the quantum aspects of high-harmonic generation.[2] It further motivated us, so we combined our expertise in quantum optics and ultrafast nonlinear optics to start exploring the generation of high harmonics using bright squeezed vacuum pulses," says Tani.

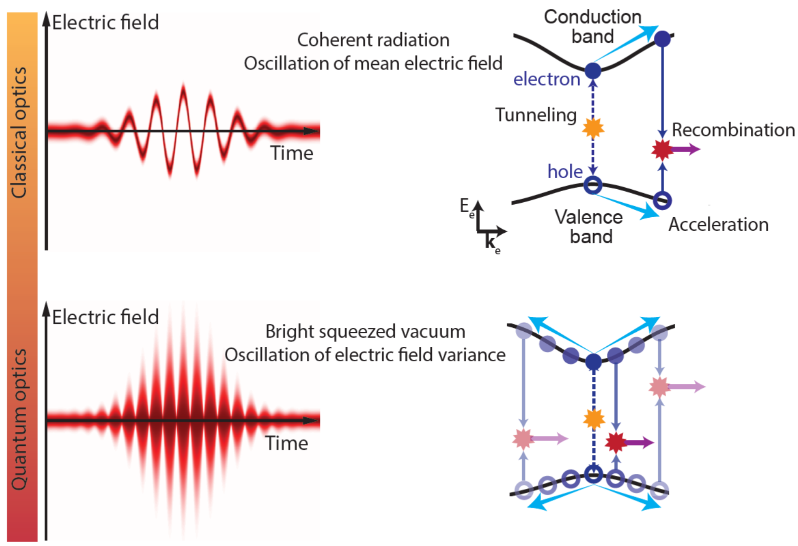
Squeezed vacuum

What's a squeezed vacuum? Light is an electromagnetic wave that



Setup for the team's bright squeezed vacuum. (Image credit: Tanya Chekhova) propagates in space and oscillates in time at a certain amplitude. Even when the amplitude is zero, according to quantum physics, it still exhibits small fluctuations known as "zero-point field or vacuum fluctuations." Think of them as random faint ripples on water's surface.

"Using strong laser pulses, we can periodically enhance and suppress these vacuum fluctuations within a nonlinear crystal to generate a quantum state of light—a squeezed vacuum," explains Tani. "By optimizing this process, we can obtain very bright squeezed vacuum states with mean photon numbers sufficiently high to drive highly nonlinear processes within a material and even ionize it."



This schematic shows the differences between classical optics vs. quantum optics for the team's work. (Image credit: Francesco Tani)

High-harmonic generation

High-harmonic generation (HHG) is a nonlinear process in which intense ultrashort pulses of light interact with matter—and it drives electrons to emit high harmonics of the driving field frequency. When the intensity of the light is sufficiently high, it drives the electrons far away from their initial state and their dynamic is no longer a small perturbation.

These nonperturbative dynamics can "alter the generation of high harmonics, enable encoding information within them, and result in multiple harmonics—even within spectral regions beyond the absorption edge of the material and lead to unique sources of radiation," says Tani.

Nonperturbative high harmonics is the foundation of attosecond science and creates unique sources of ultrashort pulses within the extreme ultraviolet and x-ray spectral regions. "This process has been accessed only by classical coherent light, but with our work we show for the first time that we can access it with quantum states of light," Tani adds. "And because of its peculiar properties, we think it's very exciting and promises access to completely new regimes and applications."

Bright squeezed vacuum pulses

A bright squeezed vacuum (BSV) provides simultaneous access to both the perturbative and nonperturbative regimes, and it also speeds up data acquisition. "With coherent light, observing the transition from the perturbative to the nonperturbative regime means we need to acquire the harmonics yields as a function of the pump power, which can be a time-consuming process," says Tani. "On the other hand, BSV contains all possible intensities and the acquisition time is considerably reduced."

One of the most interesting aspects of this work for the team was finding a common language in a scientific sense to describe the two combined research areas—ultrafast nonlinear optics and quantum optics—and understand each other," says Tani. "Both fields involve photons, but the approaches are very different. Working together and combining these research areas was very interesting and it really opened our minds."

When Andrei Rasputnyi, a Ph.D. student working with Chekhova and Tani, generated a few tens-of-femtosecond-BSV pulse with microjoule-level energies (corresponding to peak powers order of magnitudes larger than previously reported) in the lab for the first time, the team realized it meant they could access new and unexplored regimes, and similarly when he generated high harmonics for the first time via BSV.

Most important lab equipment for this work? "An old Ti:Sa laser amplifier to deliver ~40-femtosecond pulses with millijoule-level energy, but other types of femtosecond lasers may also be used for this purpose," says Tani. "The rest of our equipment is pretty standard: Nonlinear crystals, photodiodes, a CCD-based spectrometer, and various optical elements."

Biggest challenge? Identifying ways to fully exploit the quantum aspects of a BSV, which isn't straightforward because it's very susceptible to any imperfections of the optical mirrors and lenses—even dust can lead to scattering and reduce quantum squeezing.

"On short timescales, generating high harmonics using bright squeezed vacuum pulses can provide a valid route to probe the properties of matter using high-intensity light with a reduced probability of damaging the sample under study," says Tani. "In the long run, we believe it will provide a new tool for exploring the quantum properties of matter, as well as enable coupling of quantum light and quantum matter to engineer quantum states within the ultraviolet and x-ray spectral regions."

> High harmonics generated via bright squeezed vacuum pulses may serve as a new tool to explore the quantum properties of matter.

What's next?

There's a long list of experiments Tani and Chekhova want to try, but they've narrowed it down to three. First, they want to try to experimentally observe quantum light increase the number of high harmonics and extend its spectral coverage (the cutoff) as predicted by Alexey Gorlach (Technion) and colleagues in 2023.

Second, they'd like to demonstrate that BSV pulses can generate high harmonics from gaseous media to generate extreme ultraviolet radiation.

"These two experiments will provide a route to validate furter and adapt the theoretical models used to describe the interaction of nonclassical light with matter in the nonperturbative regime and may provide a promising route to extend the spectral coverage of tabletop sources of ultrashort XUV and x-ray radiation," says Tani.

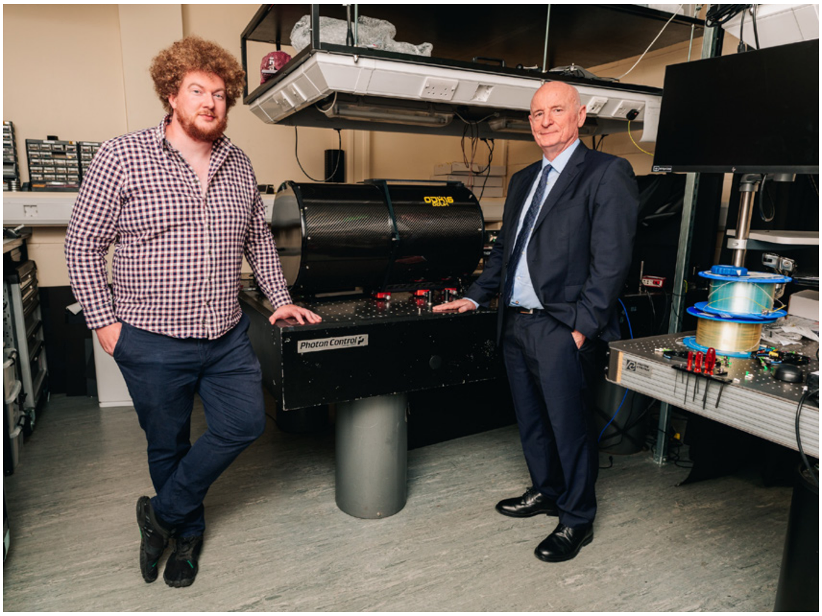
And they also want to try to use BSV pulses to drive, study, and maybe even control the dynamics of electrons within matter.

FURTHER READING

A. Rasputnyi et al., *Nat. Phys.* (2024); https://doi.org/10.1038/s41567-024-02659-x.

REFERENCES

1. A. Gorlach et al., *Nat. Phys.*, 19, 1689–1696 (2023); https://doi.org/10.1038/s41567-023-02127-y.
2. M. Lewenstein et al., *Nat. Phys.*, 17, 1104–1108 (2021); https://doi.org/10.1038/s41567-021-01317-w.



Optical ground stations push boundaries of space technology

The Hub Optical Ground Station (HOGS) based at Heriot-Watt University will feature state-of-the-art equipment—single-photon detectors and adaptive optics systems—for quantum key distribution experiments to enable development and testing of new protocols for secure satellite-to-ground quantum communications.

ROSS DONALDSON

In the rapidly evolving landscape of space technology, optical ground stations are becoming increasingly crucial. These facilities provide a vital link between Earth and satellites to enable high-speed communications, advanced research, and innovative applications.

We're taking a significant step forward with the construction of our own £2.5 million ($3.27M) optical ground station, set to become operational by the end of this year. The facility, known as the Hub Optical Ground Station (a.k.a. HOGS) and based at Heriot-Watt University, is poised to push the boundaries of space technology and contribute to the U.K.'s position as a global leader in quantum technology research.

The rise of optical ground stations

Optical ground stations gained prominence in recent years due to their ability to support high-bandwidth optical communications with satellites using laser technology. Unlike traditional radio frequency communications, optical links offer higher data rates, improved security, and reduced power consumption. These advantages make optical ground stations essential for advancing satellite communications, Earth observation, and space-based research.

Several notable optical ground stations are already in operation around the world, such as the European Space Agency's facility in Tenerife, Spain, which has been operational since 1995 and played a crucial role in various space missions and experiments. NASA's Optical Communications Telescope Laboratory at Table Mountain Observatory in California supports the agency's deep-space optical communications projects. While these facilities have made outstanding contributions to the field, HOGS will add unique capabilities and research focus areas.

Demonstration capabilities in Scotland

Scotland is experiencing a rapidly growing space industry, attracting international as well as inward investment, expertise, and employment opportunities. Universities like our

Dr. Ross Donaldson and Professor Gerald Buller pictured with equipment that will be used in the new optical ground station.

own have a pivotal role to play in this journey. There is an inherent connection between academia, industry, and innovation, and at Heriot-Watt University we are developing a space tech cluster at our research park.

Universities are not just centers of education; they are hubs of creativity, research, and development to address some of the biggest challenges facing society. Our new facility represents a comprehensive approach to space technology research—combining cutting-edge hardware with innovative research programs.

At the heart of HOGS is its role in advancing quantum communications technology. As part of the Quantum Communications Hub's in-orbit demonstrator mission (Satellite Platform for Optical Quantum Communications; SPOQC), HOGS will be instrumental in showcasing the U.K.'s academic capabilities in satellite quantum secure communications.

The facility will feature state-of-the-art equipment for quantum key distribution experiments, including single-photon detectors and adaptive optics systems. This will enable us to develop and test new protocols for secure satellite-to-ground quantum communications, a critical area for future cybersecurity applications.

Versatile infrastructure

HOGS boasts a comprehensive set of infrastructure that makes it highly adaptable for various research purposes, including a 4.5-m-diameter clamshell-style observatory dome, a 70-cm-diameter optical terminal with a Nasmyth observatory telescope, two 100-kg ground payload capabilities, and a 40-cm-piggyback telescope with visible and infrared cameras for coarse tracking and space imaging.

Environmental monitoring tools will measure local conditions, including atmospheric turbulence. This versatile setup allows us to support a wide range of missions and observations, from quantum communications experiments to space debris tracking and astronomical observations.

Integration with campus network

Unlike many standalone optical ground stations, HOGS will be directly connected to a campus-based dark optical-fiber network. This integration links the facility with local academic buildings and a lab-based network simulator to provide access to next-generation quantum and photonic systems essential for quantum networking research.

> HOGS will advance quantum communications technology and push the boundaries of what's possible in space technology.

The network simulator offers point-to-point links ranging from 10 to 300 km, which allows us to test and develop technologies for future quantum networks in a controlled environment before deploying them in real-world scenarios.

Multi-mission capability

While quantum communication is its primary focus, HOGS supports a variety of space-related research areas like optical communications. We will be exploring high-bandwidth capabilities for future satellite communications systems, as well as testing space situational awareness, leveraging our northern location for excellent visibility of satellites and debris within low-Earth polar orbit.

Finally, we will be exploring astrophotonics by testing new photonic devices for improved astronomical measurements. This multi-mission approach ensures that HOGS will remain at the forefront of space technology research for years to come.

Advancing the U.K.'s space capabilities

The development of HOGS aligns with broader initiatives to strengthen the U.K.'s position within the global space sector. It complements other investments in quantum technology research and development, such as the recently announced Integrated Quantum Networks (IQN) Hub, which aims to develop technologies for an ultrasecure quantum internet of the future.

By providing a world-class facility for researchers and industry partners, HOGS will play a crucial role in fostering collaboration between academia and industry as well as training the next generation of space technology experts.

Other U.K. researchers with relevant interests in experimental satellite quantum communications will be invited to work onsite using the modern telescope to track satellite paths with high precision. Heriot-Watt students, from undergraduate to Ph.D., will benefit from the new capabilities, and local school children can be hosted onsite to build their knowledge and understanding of satellite communications and astronomy.

Challenges and opportunities

As we embark on this exciting journey, we're mindful of the challenges that lie ahead. Developing

(L-R) Graham McPhail, Professor Gillian Murray, Dr. Ross Donaldson, and Professor Gerald Buller on the site of the new optical ground station. (Photo credit: Heriot-Watt University)

and operating a cutting-edge optical ground station requires overcoming technical hurdles, navigating regulatory landscapes, and addressing potential environmental concerns.

But these challenges also present opportunities for innovation. For instance, developing new adaptive optics techniques to mitigate atmospheric turbulence effects on laser communications, creating more efficient and sensitive single-photon detectors for quantum communications, and designing novel algorithms for space debris tracking and identification.

By tackling these challenges head-on, we aim to push the boundaries of what's possible in space technology and contribute to solutions that benefit not just the U.K., but the global scientific community.

Looking to the future

As we approach the completion of HOGS in 2024, we're already looking ahead to its potential impact and future developments. These include connecting HOGS to a Scottish Quantum Network, linking universities and business centers across Scotland's Central Belt, integrating with the U.K. Quantum Network and other global networks to facilitate international collaborations, and exploring new applications in fields such as Earth observation, climate monitoring, and deep-space communications.

We believe HOGS will serve as a catalyst for innovation within the U.K. space sector to drive advancements in quantum technologies, optical communications, and space situational awareness.

As we move forward, we invite researchers, industry partners, and space enthusiasts to join us on this exciting journey. Together, we can push the boundaries of what's possible in space technology and contribute to a more connected, secure, and technologically advanced future.

Ross Donaldson leads the Optical Ground Station project at Heriot-Watt University. With expertise in quantum communications and photonics, he is dedicated to advancing space technology research and fostering collaboration between academia and industry. The facility is being built as part of the Quantum Communications Hub project, funded through the U.K. National Quantum Technologies Programme and is part of a collaborative effort which also involves the Universities of Bristol, Strathclyde, and York. Space engineering expertise is provided by the Science and Technology Facilities Council's RAL Space Facility.

IBM envisions classical and quantum computing 'blend' for quantum-centric supercomputing

In a Q&A with IBM Distinguished Research Scientist and Quantum Engine Lead Blake Johnson, he brings us up to speed on their latest quantum utility advances, unpacks Heron/Qiskit, challenges blending classical and quantum computing, and shares what they're working on now.

Quantum Innovators: **Can you introduce us to IBM Heron/Qiskit and explain why it's a step forward for the quantum realm?**

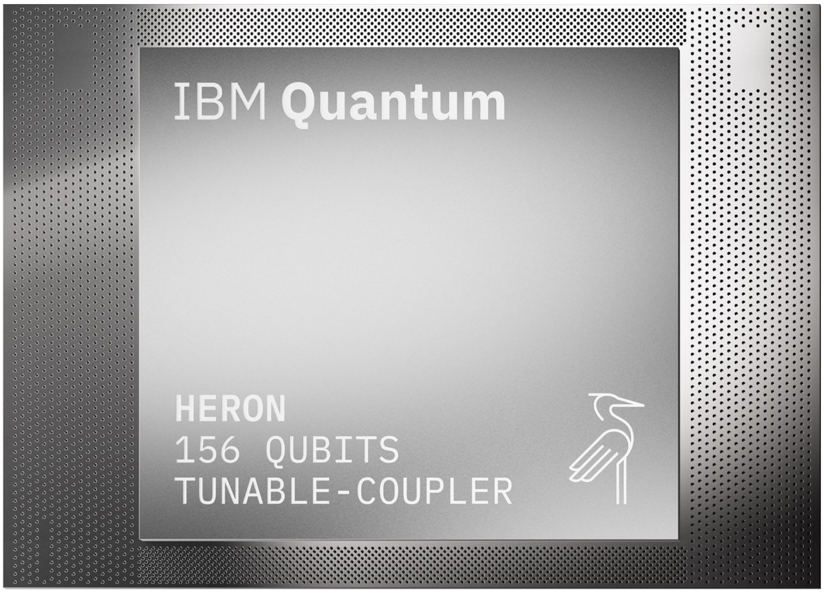
Blake Johnson: IBM Quantum Heron is our most performant processor to-date. As announced at the IBM Quantum Developer Conference, Heron is now capable of executing certain quantum circuits of up to 5,000 gate operations—nearly twice the number of gates accurately run in the IBM's 2023 demonstration of quantum utility published in *Nature*. And, with improvements to our Qiskit software, it can also run the 2023 utility demonstration 50x faster.

In addition to these performance improvements over the 2023 utility demonstration, IBM Heron offers up to a 16-fold overall improvement in performance and 50-fold increase in speed over previous IBM quantum computers as they were measured two years ago.

This Heron processor is now available to our clients, and installed in systems at our data centers in Poughkeepsie, New York, and Ehningen, Germany, IBM's first quantum data center in Europe.

Qiskit, the world's most popular quantum software platform, is purposely built to extract the best performance from real quantum hardware as industries across the globe build and discover new quantum algorithms in the search for quantum advantage: the point at which a quantum computer offers the best way to solve a problem over any classical method.

As we extend the reach of reliable execution to larger and larger quantum circuits, we increase the scope of applicability of quantum computing to a broader set of problems. This is a critical prerequisite technology to enabling application and algorithm development in search of quantum advantage.



IBM Quantum Heron r2 is the second gen (r2) of IBM Heron processors.
(Image credit: Ryan Lavine for IBM)

***QI:* Can you explain why hitting 5,000 gates is a milestone? What does it mean for security?**

Johnson: The combined improvements across IBM Heron and Qiskit extend our users' ability to reliably execute certain quantum circuits of up to 5,000 gates, which is nearly twice the number of gates accurately run in IBM's 2023 demonstration of quantum utility. The Qiskit stack now includes a third-generation runtime that enables executing the 2023 utility experiment up to 50x faster, reducing the time to execute it from 112 hours to 2.2 hours.

Our clients and partners are already exploring—and delivering—on capabilities operating at a similar scale. For example, Algorithmiq's tensor error network mitigation (TEM) method, which is available through the IBM Qiskit Functions Catalog, offers state-of-the-art error mitigation for circuits at utility scale and is capable of supporting circuits with up to 5,000 entangled quantum gates.

Achieving 5,000 gate operations builds on what the broader quantum community has already published with utility-scale experiments. And other Qiskit Functions providers, like Algorithmiq, that have delivered their own capabilities will be able to push the accuracy and scale of quantum circuits to drive algorithm discovery further.

Regarding security, IBM also has the goal of making the world quantum-safe. As our users progress toward advantage, we are also advancing toward potentially cryptographically relevant quantum computers, which could crack today's encryption in the future. The good news is today's quantum computers are not cryptographically relevant, but we need to start preparing now. And quantum-safe cryptography exists today—including two IBM-developed PQC algorithms NIST recently published as its first three algorithms as official post-quantum cryptographic standards.

IBM's Quantum System One at Rensselaer Polytechnic Institute. It was unveiled in April 2024 in RPI's Voorhees Computing Center, a former cathedral, and is the first to be installed on a university campus. (Image credit: IBM)

***QI:* How does Qiskit help quantum developers/researchers?**

Johnson: IBM developed Qiskit into the world's most performant quantum software to enable quantum developers and researchers to more easily create complex quantum circuits with enhanced stability, accuracy, and speed. Qiskit equips more than 600,000 users and more than 250 members of the IBM Quantum Network with the capabilities needed to discover the next generation of quantum algorithms, which will be the crux of their discovery of quantum advantage.

And the Qiskit Functions Catalog is available to IBM Quantum Premium Plan users as services that allow those users to abstract away parts of the quantum software development workflow, which we believe will speed up algorithm and application development.

***QI:* Biggest challenges involved in connecting quantum and classical supercomputers?**

Johnson: To build the next generation of algorithms, users need a toolset to map their problems in a way that leverages both advanced classical and quantum computation, optimizes the problem for efficient execution with quantum, and then effectively executes the quantum circuits on real quantum hardware.

As IBM continues to build milestones along its IBM Quantum Roadmap toward error-corrected systems, Qiskit will continue to deliver a framework for open, iterative, and collaborative development of new quantum algorithms and applications—in conjunction with a growing global ecosystem of clients across industries and domain expertise areas.

These advancing capabilities aim to help users weave together classical and quantum computing resources into a new paradigm of high-performance computing defined by quantum-centric supercomputing that combines quantum processing units (QPUs), graphics processing unit (GPUs), and central processing units (CPUs).

Orchestrated through the performant software layer of Qiskit, this next evolution of high-performance computing aims to open new, large, and powerful spaces for industries globally.

We also announced at our IBM Quantum Developer Conference that Rensselaer Polytechnic Institute (RPI) is using Qiskit tools to take the initial steps to build IBM's first realization of quantum-centric supercomputing on a university campus. RPI and IBM aim to successfully connect workloads across the AiMOS classical supercomputer and IBM Quantum System One, both located on RPI's campus, into a single computational environment managed by a standard high-performance computing resource manager.

***QI:* Power requirements to run Heron/Qiskit?**

Johnson: Quantum computer power consumption comes down to the cryostat, control electronics, and runtime on classical servers. Power usage for a quantum computer must be compared to the power usage for a similar workload on a classical computer. In general, quantum computers are expected to consume significantly less power in the future because significantly less time is required to run the workload (a utility scale or future quantum advantage workload).

***QI:* What's next?**

Johnson: IBM's Quantum Development Roadmap aims to realize error-corrected quantum computers at scale while continuously advancing the near-term scientific value of today's systems. This will progress us further into the era of quantum utility and quantum algorithm discovery, and into the era of quantum-centric supercomputing.

IBM's vision of quantum-centric supercomputing will enable both paradigms of computing—classical and quantum—to work seamlessly together with performant software to solve different parts of complex computing problems that are best suited for their respective strengths and capabilities.

Quantum Corridor expands quantum comms network plans

In this Q&A with Quantum Corridor's CEO Thomas P. Dakich, he shares what it's like to launch a quantum network, challenges involved, how the project's goals quickly expanded, and what's next.

Quantum Corridor is an ambitious project to build a quantum-ready fiber-optic communications network to enable quantum innovators in Indiana and Illinois to exchange data nearly instantaneously—and it's already expanded since we first talked to them a few months ago.

The network originates in Hammond, Indiana at the Digital Crossroads Data Center, and stretches 22.5 kilometers (14 miles) to Chicago's ORD10 Data Center. An expansion is now in the works to extend the network from Hammond to Crane Naval Surface Warfare Center and Crane West Gate in Southwest Indiana.

In a cool move, 423.2 kilometers (263 miles) of new and existing fiber-optic cable beneath the Indiana Toll Road will be tapped to link data centers, quantum research facilities, researchers and scientists, and hyperscalers with quantum speeds and throughput.

Quantum commercialization centers are planned along the network's route to house entanglement nodes, which will serve as relay points to ensure transmission efficiency. These facilities will also be mini data centers where customers, researchers, and students have access to work and learn.

Quantum Innovators: **What does it take to launch a project like this?**
Thomas P. Dakich: Any time you attempt to transform the thinking of an entire state, it's very difficult. So many people in leadership positions across the country are conflicted about the role of science and the role each state should play in promoting science solutions to relatively complicated problems.

Creating a fiber network to connect computers that don't even work yet is quite challenging! As quantum research and computing continues to grow, networking these companies and computers together will become the most important way for advanced human research to move forward. I never want any person of leadership at either the state or the federal level to think they didn't understand our project and, as a result, be against it. Our biggest challenge is to make certain people in leadership know what we're doing and that they're making informed decisions about support for our efforts.

Thomas P. Dakich, CEO of Quantum Corridor.

QI: **How did you go about getting funding?**
Dakich: Very early in the process, we hired an excellent and experienced investment banker to secure our first round of funding. Our pre-funding came from president and CTO Ryan Lafler, me, and the State of Indiana. We also used assets already available to secure more support for bigger parts of this project. We've closed our Round 1 and are now in our $140 million Round 2. Our eventual capitalization will exceed $7.7 billion.

QI: **Any advice for others who'd like to launch a similar project?**
Dakich: The expansion of technology during the second half of this decade will be much easier than it

Digital Crossroads Data Center in Hammond, Indiana.

was the first half. Access to funding for these second and third groups of entrepreneurs will be markedly easier than it was for the first groups. This is how it works. I honestly believe quantum computing is going to change the trajectory of human thought, and problems we have today will be laughable compared to the solutions we are creating. My theory is the more money and people we get on board with the importance of what we are doing, the better!

***QI:* Any goals shift for the project since you started?**

Dakich: We started out thinking about connecting Indiana and Illinois in one network and now we've moved across the country and south to catch more groups and research institutions doing important work. The project just keeps expanding and getting bigger.

***QI:* How is the Crane Naval Surface Warfare Center involved?**

Dakich: Phil Smith and the people at Crane are amazing proponents for what we're doing, and the work done by former Indiana Governor Mitch Daniels to secure the long-term future of Crane by promising to build a highway has sustained Crane as an important part of all defense research. The next connectivity points will not be surface roads, but rather quantum internet and advanced technology networking. We wake up every day with the mission to connect Crane with the highest level of connection back to those across the country who are doing the most important research in the world.

***QI:* What's next?**

Dakich: Our network will connect Crane back to Chicago, connect Purdue back to both Crane and Chicago, and then connect both institutions to a whole defense and research infrastructure across the country. We're just at the start of this networking revolution that is underway in quantum—and we are thrilled to be early.