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features

Quantum Research & Innovation: Welcome!

I'm thrilled to welcome you to the first issue of *Quantum Research & Innovation!*

There are so many intriguing research & development (R&D) advances going on within the quantum realm—all at once, everywhere around the globe—that it's nearly impossible to keep up with them all. But we'll bring you as many of the coolest ones as we can via a mix of contributed articles and staff-written features.

We'll also introduce you to quantum companies and people doing amazing things within this space, and provide analyst updates about how the quantum realm and its supply chain are evolving.

It's truly mindbending how much quantum R&D is underway—and its potential to revolutionize so many fields.

In this issue, our cover story highlights quantum-inspired phase imaging work led by Radek Lapkiewicz's Quantum Imaging Lab at the University of Warsaw in Poland—and a big thank-you to Jerzy Szuniewicz for our fantastic cover image!

We also have fabulous contributed pieces from Quantum Science and Alice & Bob, an introduction to Vescent and Quantum Corridor, and a timely quantum supply chain update from Doug Finke of Global Quantum Intelligence.

To anyone who loves physics, photonics, or simply wants to learn more about quantum R&D: this one's for you.

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Watching over the quantum technology supply chain

The quantum supply chain is still in its nascent stage—and these are the key trends to keep an eye on as it evolves.

DOUG FINKE

The quantum supply chain is currently in a nascent stage, characterized by high demand for advanced products that necessitate extensive R&D, leading to elongated lead times that impede progress. While quantum computing has the potential to revolutionize how such things as supply chain are managed, its own supply chain is still filled with uncertainty. The market is marked by a small volume of highly specialized quantum products, which faces a "valley of death" without adequate government subsidies and support.

Traditional industries are entering the quantum domain through investments in quantum computing, sensing, and communications technologies. Their entry is shaping the quantum supply chain by integrating conventional manufacturing prowess with quantum innovation.

Stakeholders can position themselves by investing in R&D, forming strategic alliances, and adopting a multi-sourcing strategy to mitigate risks associated with the quantum supply chain. Emphasizing collaboration, both within and across borders, is crucial to building a robust quantum ecosystem.

There is a driving need for policymakers, investors, and vendors to connect, support, and streamline the chaos of innovation into the clarity of solutions.

Global quantum supply chain report

To provide answers for this diverse audience, Global Quantum Intelligence (GQI) created an in-depth market study and report of the Global Quantum Supply Chain.

Image credit: GQI

better understand the very complex quantum supply chain. Policymakers need to make strategic decisions that can spark progress. Investors want to look out for the next big leap. And vendors need to best understand customer requirements, competitions, and other factors efforts to

We identified 744 suppliers located in 36 different countries supplying 60 different types of components, grouping them into categories such as photonics, electronics, cryogenics, mechanics, and several other areas.

As part of the study, we also interviewed several purchasers of these

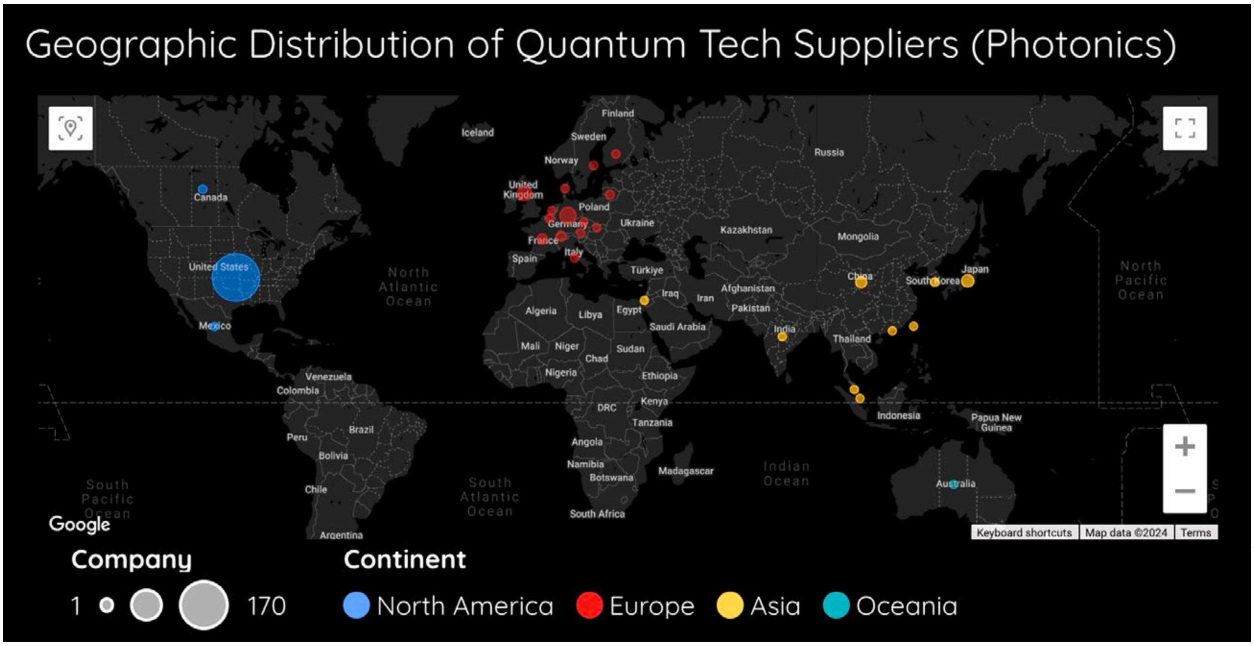


Image credit: GQI

components to identify significant macro trends and challenges they face in obtaining a stable supply for their needs. To help our users gain a better understanding of this ecosystem, we created a framework that can help classify the components in several dimensions—including quantum pillar (computing, communication, or sensing), quantum platform (e.g., superconducting, ion trap, photonics, criticality, country of origin, size of company, and supply chain value).

To make this information available to our customers, we provide a full report on the supply chain as well as an interactive, dynamic display that allows a customer to filter and organize the data to serve their needs. Sample screen shots of the dynamic displays are shown below.

General observations

Here are some of the key findings we found in our research relevant to all segments of the quantum supply chain and discussed in the report:

1. Lead times are a critical bottleneck due to the surge in demand for high-end quantum products, necessitating a multi-sourcing strategy.

2. The quantum sector is grappling with the "small volume problem," requiring government intervention and subsidies to traverse the "valley of death."

3. For quantum technologies to thrive, funding distribution must be balanced across the ecosystem, recognizing the dependencies of software and hardware.

4. The Western quantum supply chain exhibits strength and resilience, with countries specializing in niche areas and fostering regional ecosystems.

5. The supply chain is diverse, encompassing both established corporations and burgeoning startups, each contributing unique value.

6. Standardization and consolidation are imperative to streamline operations and ensure compatibility across the quantum supply chain.

7. The industry has yet to reach the era of scaling and commercialization, indicating that the current focus remains on development and prototyping.

Key developments to watch

The quantum supply chain, like the rest of the quantum industry, is very dynamic with new offerings and vendors being introduced every week. GQI is keeping a close eye on what is happening and the list below shows some of the key developments to watch:

1. The timeline for scaling and commercialization of quantum computing, sensing, and communications technologies remains uncertain.

2. Potential shortages of crucial elements like Helium-3 could create supply constraints, impacting the progress of superconducting qubits.

3. Governmental roles in providing funding subsidies and allocating critical resources for quantum development are yet to be fully realized.

4. International cooperation vs. national-centric approaches in quantum development will shape the future landscape of quantum technology.

5. The establishment and adoption of standards for quantum technology are still in the formative stages, with significant advancements required.

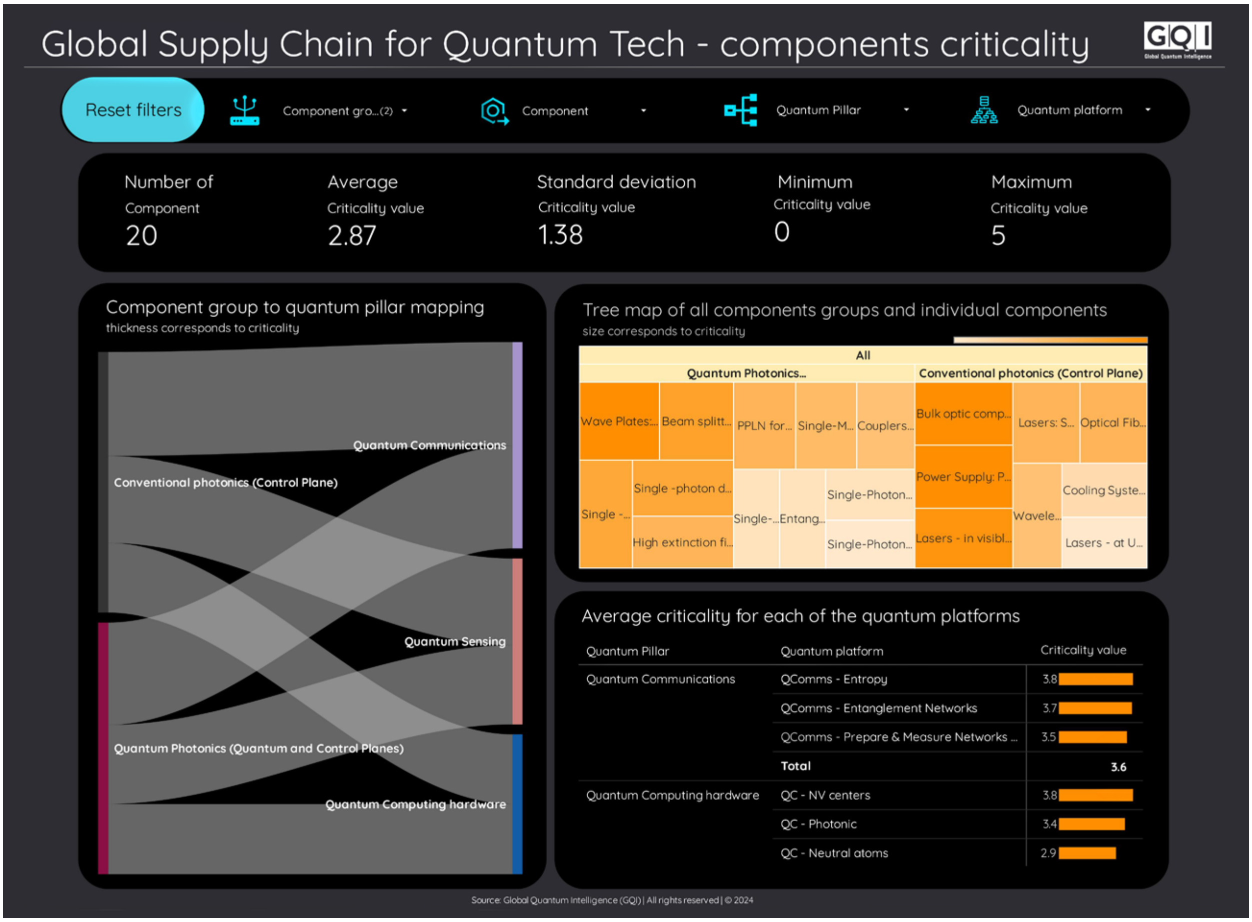


Image credit: GQI

Photonic components

In addition, when we look specifically at photonics components we can make some additional comments. Photonics splits into two categories: Conventional Photonics, focusing on lasers (UV, visible light, SWIR) and related equipment, and Quantum Photonics, which emphasizes single-photon sources, detectors, and their associated gear.

Across these categories, there are 20 component types relevant to quantum technology. Their criticality varies widely, with an average level deemed medium, but with a range from 0 to 5—indicating components that range from easily replaceable or abundantly available to those irreplaceable without significant detriment to development.

The Sankey chart analysis reveals that both Conventional and Quantum Photonics hold comparable importance across the three main areas of quantum technology, with a similar criticality distribution.

> These findings and developments paint a picture of a quantum supply chain that is ripe with potential.

Quantum Communications is highlighted as the most photonics-dependent area, though Quantum Sensing and Computing also significantly rely on photonics technologies.

Geographically, the United States stands out as a major photonics hub, with Germany, specifically the Berlin region, also noted for its well-developed photonics ecosystem. In Asia, Japan and South Korea are recognized as key players in the field.

These findings and developments paint a picture of a quantum supply chain that is ripe with potential, yet faces significant hurdles that must be addressed through strategic planning, collaboration, and policy support. The full report spans 50 pages and provides an in-depth look at what is happening in this complex quantum supply chain. To learn more, you can visit the GQI website at https://global-qi.com.

Doug Finke is the chief content officer for Global Quantum Intelligence (GQI), a business intelligence firm for quantum technology; e-mail: doug@global-qi.com; https://global-qi.com.

| QUANTUM IMAGING |

Quantum-inspired phase imaging is immune to instabilities

Image credit: Jerzy Szuniewicz

Researchers prove interferometric imaging is possible even within extremely dark and unstable conditions where intensity fringes can't be seen.

SALLY COLE JOHNSON, SENIOR TECHNICAL EDITOR

A quantum-inspired phase imaging method based on light intensity correlation measurements created by a team of researchers led by Radek Lapkiewicz's Quantum Imaging Lab at the University of Warsaw, along with colleagues from Stanford University and Oklahoma State University, is robust to phase noise—which means it operates even under unstable conditions and extremely dim illumination.

Standard images are captured by measuring the intensity (brightness) of light pixel by pixel. Light is characterized its intensity and phase, and transparent objects can become visible if you measure the phase delay of light they introduce.

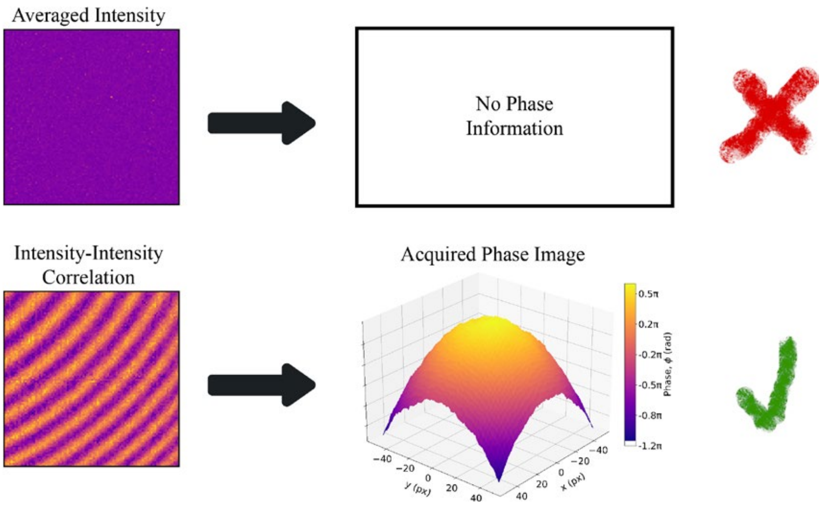
The team's phase imaging method was inspired "by the works of Leonard Mandel on the interference of independent sources and Hong-Ou-Mandel effect—especially when generalized to spatially dependent phase profiles of photons," says Jerzy Szuniewicz, a Ph.D. student at the University of Warsaw. "Observation of spatial phase dependence on the Hong-Ou-Mandel effect made us wonder if there's a classical equivalent of this quantum effect, and it's how we got our idea."

In the 1960s, Mandel and his group showed that even if interference isn't detectable in intensity, correlations can reveal its presence. So Lapkiewicz's team decided to explore how intensity correlation measurements can be used for phase imaging.

For a correlation measurement, researchers examine pairs of pixels to see if they get brighter or darker at the same time.

And the team showed these measurements contain more information than can be obtained via a single photo, such as intensity measurement. The researchers went on to use this to demonstrate that in phase imaging based on interference, observations are possible even when standard interferograms average out losing all the phase information and no fringes are recorded in the intensity.

"With a standard approach, we'd assume there's no useful information in such an image," says Lapkiewicz. "But it turns out information is hidden within the correlations and can be recovered by analyzing multiple independent photos of an



Comparison between averaged intensity and correlations from the experimental data for a 2D spherical phase. Averaged intensity doesn't carry any phase information (top), but correlations (bottom) have high visibility interference fringes that allow the researchers to reconstruct the spatial phase. *(Image credits: University of Warsaw)*

object—which allows us to obtain perfect interferograms, although the ordinary interference is undetectable due to the noise."

Intensity-intensity correlation experiment

In the team's experiment, light passes through a phase object—a target being explored—and is superimposed with a reference light. A random phase delay is introduced between the object and the reference light beams, which simulates a disturbance obstructing standard phase imaging methods.

No interference is observed when the intensity is measured, which means no information can be obtained about the phase object from the intensity measurement. But, intriguingly, the spatially dependent intensity-intensity correlation displays a fringe pattern that contains the complete information about the phase object.

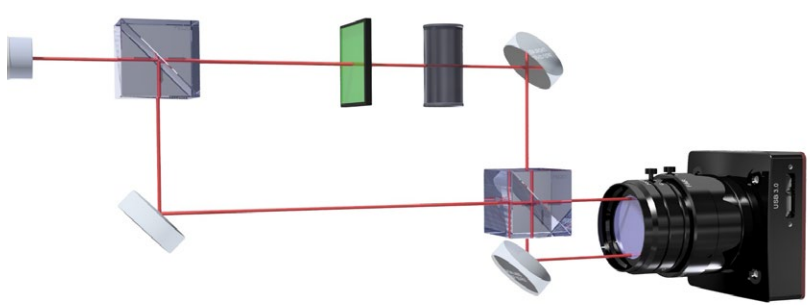
It turns out this intensity-intensity correlation "is unaffected by any temporal phase noise varying slower than the speed of the detector—~10 nanoseconds for our experiment—and can be measured by accruing data over an arbitrarily long time period, which is a gamechanger," explains Szuniewicz. "A longer measurement means more photons, which translates to greater accuracy."

If they recorded a single film frame, it would provide no useful information about the object being studied. So the team recorded a series of frames using a camera, and then multiplied the measurement values at each pair of points from every frame. Averaging these correlations provides a full image of the object.

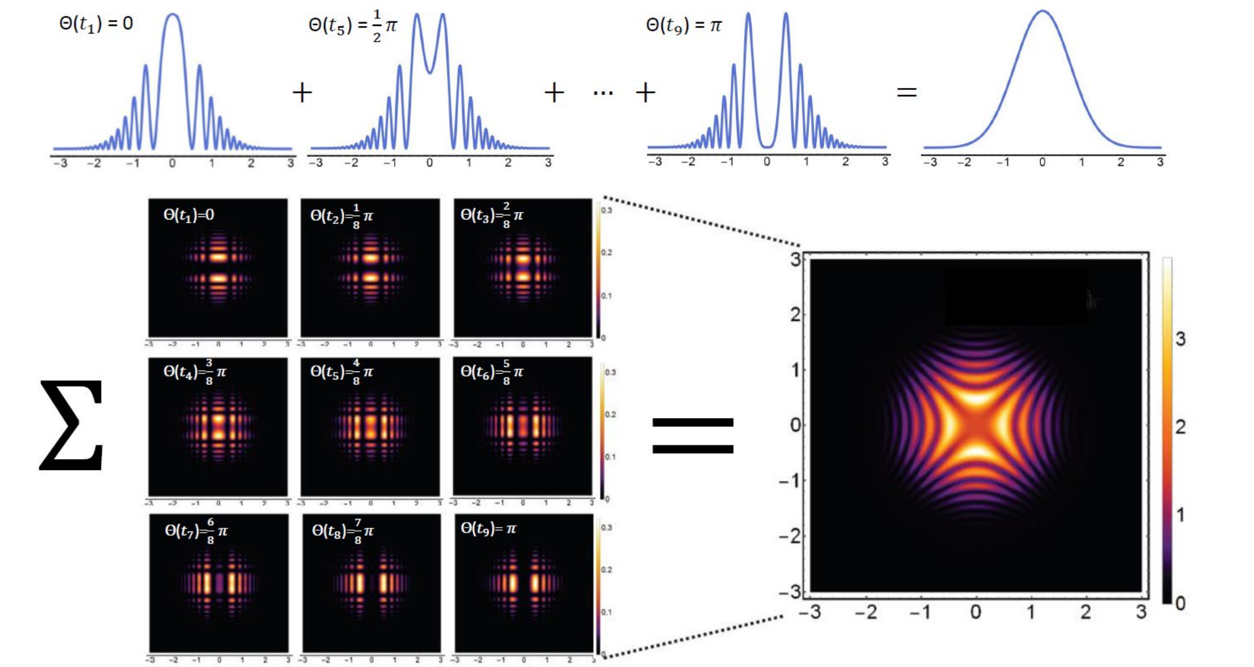
"We combined standard interferometry with intensity correlation measurements, then we simply averaged these correlations to get our phase imprinted onto the measured correlations," says Szuniewicz. "Our setup is just an interferometer with a target phase and a phase-noise source—with a twist of clever data analysis. And the correlation method works for any interference phenomenon."

The team proved that their method based on intensity-intensity correlation and an off-axis holography technique is optimal for reconstruction precision. Their method works well for any light statistics—such as single photons, thermal light from a lightbulb, or coherent light from a laser—and this is its greatest advantage.

A big surprise was in store for the researchers when they realized the effects observed by Mandel have implications for standard interferometry and phase imaging. "The beauty and simplicity of the math describing the phenomena is amazing—a first-year student can derive it," says Szuniewicz. "And it's optimal—there's no way to get more information from the data than we obtained. We proved it by using the



Schematic of the experimental setup used in the experiment. Light is divided into two paths. The measured (spatial) phase is introduced in one arm of the interferometer, along with a fluctuating phase noise. Interference is observed on a camera and the correlations are calculated from the experimental data.



Schematic comparing intensity average (top) and average of correlations (bottom) for the same phases. The standard intensity average has no information about the phase, while the averaged correlation has the full information about the phase of the photon.

Cramer-Rao bound, which shows that the information extracted with our method is equal to all of the information present in the experimental data. It's cool when you reach this ultimate precision."

One of the biggest challenges the team faced with this work was journal editors and reviewers who essentially pushed them to perform experiments for two-dimensional (2D) phase masks.

> Their method has an extremely wide range of potential applications in phase measurements.

"We avoided it because 2D phase reconstruction using this method, to be optimal, requires us to work in a four-dimensional (4D) space," says Szuniewicz. "It was a challenge to analyze the data and understand how to interpret the results. But the 2D phase retrieval worked much better than we anticipated and helped us show the noise removal feature of our method."

Applications for dark environments

A phase imaging approach based on intensity correlation can be used widely within very noisy environments, and the team's method works with both classical—laser and thermal—and quantum light. This means their method has an extremely wide range of potential applications in phase measurements, including emerging applications such as infrared and x-ray imaging and quantum and matter-wave interferometry.

The applications are "countless," Szuniewicz says with a laugh. "Our method can help with precise measurements of interference everywhere phase stability is a problem. It works for visible light, but also for more exotic interference like x-rays or even matter waves."

It may also find applications in photon counting, for example, using single-photon avalanche diodes. It's ideal for cases in which little light is available or when high light intensity must be avoided to prevent damage to objects like a delicate biological sample or a work of art.

"I'd be thrilled to see our technique applied to matter-wave interferometry or exotic spectral ranges such as x-rays—we're always happy to discuss it, so if you have ideas let us know," says Lapkiewicz.

Remote sensing seems to be "a natural scenario where interference fringes are extremely challenging to observe," Lapkiewicz says, "and our technique can help to see them in intensity correlations."

FURTHER READING

J. Szuniewicz et al., *Sci. Adv.*, 9, 38 (Sep. 22, 2023); doi:10.1126/sciadv.adh5396.

Quantum materials are revolutionizing imaging and sensing

The quantum revolution is underway and quantum dots are enabling imaging and sensing applications previously considered too cost-prohibitive or bulky.

HAO PANG

Applications long dominated by expensive, bulky technology are now becoming possible at a fraction of the price. From machine vision to gas detection, sensors that tap into infrared (IR) wavelengths are growing more accessible by the day, enabling cameras to "see" beyond the visible and harness vast quantities of data. As demand for IR sensing grows over the next decade, the technology powering this breakthrough—quantum dots (QDs)—is only becoming more advanced, bringing high-performance capability hurtling into the market.

The quantum revolution is truly underway.

What are QDs?

QDs are nanoscale semiconducting materials that absorb and emit different wavelengths of light depending on their size. The key to controlling QD growth is how they are produced. Most are made using long-chain organic ligand exchange, which helps them to keep their colloidal stability when immersed in solvents. Because they measure just a few atoms wide, QDs benefit from an increased quantum confinement effect. In principle, this means QDs act as a small semiconductor box and, as the size of this box shrinks, the quantum confinement effect increases and band gap between the valence state and conduction band is increased. Tuning the size of QDs results in extremely tunable absorption and emission wavelengths.

High-performance QDs can be tuned to absorb and emit light all the way from the visible, through near- and short-wave IR (NIR and SWIR) to mid-wave IR (MWIR). This grants them unmatched flexibility across multiple spectra and outstanding sensitivity, particularly for SWIR sensing applications—matching or surpassing the best widely available alternatives.

Smaller size, lower cost

QDs can be produced at kilogram scale and still offer the level of performance required for imaging and

A scientist inspecting quantum dot films using an optical microscope.
(Photo credits: Quantum Science)

sensing applications. Modern QD synthesis removes the requirement to deposit the materials in 14 to 16 layers, with sequential chemical “spin-coating” treatments between each stage.

Instead, QD surface-treated ink can be deposited in a single layer. This eliminates the need for extensive chemical processing and minimizes the risk of defects such as cracking or inefficient exchange processes that occur in the films that plague other deposition methods.

Using this strategy for QD deposition significantly cuts the time and waste involved in production. As a result, high-performance QD ink can be produced at a cost-effective scale.

To date, indium-gallium-arsenide (InGaAs) has dominated SWIR sensing and imaging applications due to the high performance it offers. But InGaAs is not without its drawbacks: it often costs up to $10,000 per unit. This price is inflated due to the high rate of defects that occur during batch production, which is something that QDs easily overcome.

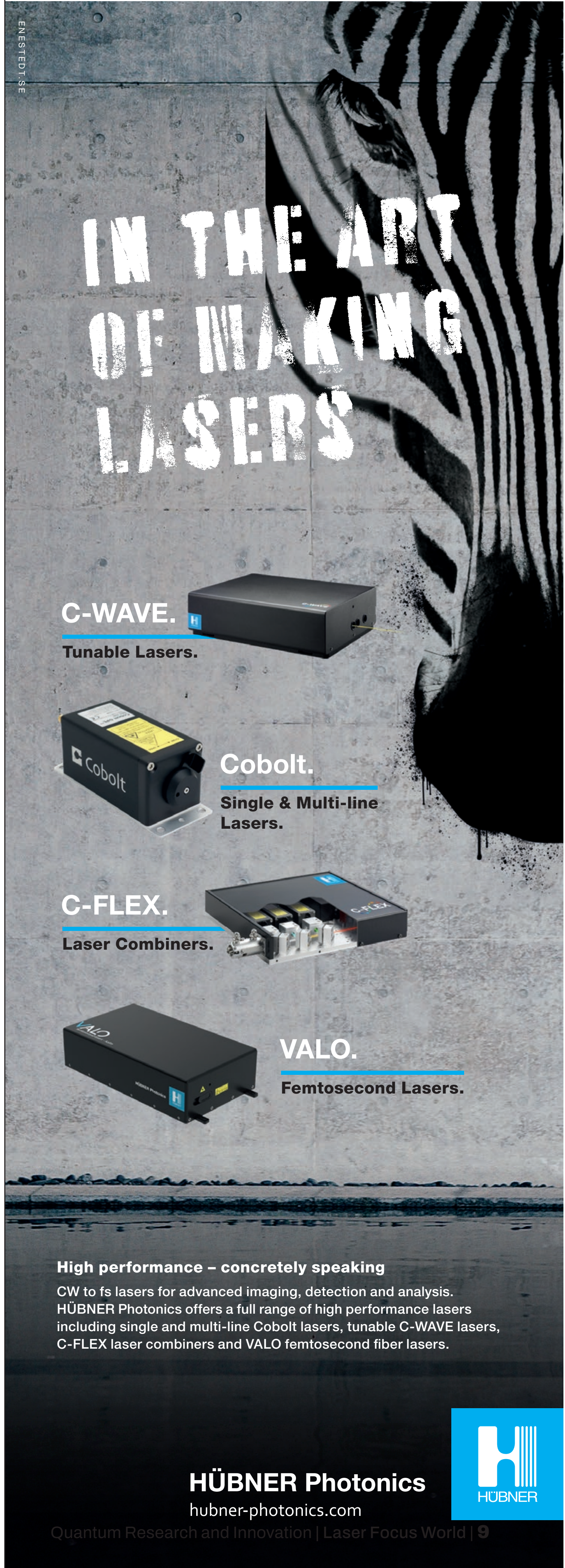
InGaAs sensors are created by growing the material directly onto indium phosphide (InP) wafers, which are diced into chips. Pixels are then indium bonded with silicon readout circuits, but it results in limited pixel pitch and resolution, and the fragility of InP materials makes it challenging to create larger wafers. Copper-copper hybrid wafer bonding technology offers an alternative production method, but results in sensors that are even more susceptible to noise due to the high dark current they experience at room temperatures.

Bulky cooling systems are also required to ensure these systems can deliver required performance standards, which further increases the cost of production. Combined, this means that QDs often cost anywhere between 100 and 1000x less than equivalent InGaAs solutions, but they still offer comparable or superior performance for imaging and sensing.

Practical applications

In many ways, SWIR acts like visible light. Where it differs is in its response to certain substances like water and plastic. For example, some SWIR wavelengths are absorbed by water, which produces dark areas on images captured by a SWIR camera, and some plastics and silicon appear transparent under SWIR light.

These characteristics grant SWIR outstanding applications for machine vision. Cameras that integrate SWIR QD technology can be used to monitor fill levels inside opaque plastic containers or detect subdermal



A scientist preparing a quantum-dot photodiode device for electrical measurement in a nitrogen-filled glove box.

bruising in food with high water content, because any bruises will appear darker than the surrounding area under SWIR light.

SWIR sensors powered by QDs can also help companies to protect their workforce and reduce their environmental impact by enabling high-performance gas detection. As demand for air pollution monitoring equipment grows, driven by the increasing recognition of the dangers posed by gases like methane (CH_4), many companies are seeking low-cost, lightweight solutions to help them identify where emissions are occurring.

Hyperspectral imaging is an invaluable tool for this application. The absorption characteristics of CH_4 make it easily identifiable under SWIR light, which ensures detectors can pick up even small traces. The high quantum efficiency of SWIR QD detectors and low read noise at room temperature further enhance its effectiveness as a monitoring solution.

Researchers are experimenting with using QDs to sense gas in a different way. Many gas sensors used


A scientist operating an atomic force microscope (AFM) used to measure properties of quantum dot films.

today use nanostructured metal oxides due to their high surface-to-volume ratio and reactivity, but they suffer from limited selectivity and require high temperatures to work effectively. The large effective surface-to-volume ratio of QDs results in high chemical reactivity with certain chemicals, which creates effective chemiresistors with resistance linked to the concentration of the gas being measured for. And the outstanding processability of QDs means they are suitable for use on a range of different substrates.


A quantum dot film deposited onto a glass substrate that has been scratched to allow measurement of the thickness.

Bringing QDs into the mainstream

One of the most common barriers to widespread QD rollout is the inherent toxicity of the highest-performing materials. Most QDs include heavy metals such as lead or cadmium to maximize their efficiency, but these elements are restricted for use by leading manufacturers and subjected to potential future regulation restrictions. Alternative formulations are available that substitute heavy metals for materials like indium, but they struggle to match the performance of traditional solutions.

The best-performing lead-free QDs are sensitive to wavelengths up to approximately 1550 nm and provide suitable non-lead QD alternatives for a wide range of SWIR sensing applications.

QD technology is not some distant, far-off concept—it is already being used for multiple machine-vision applications today, which provide a low-cost alternative to existing InGaAs sensors. QD-based devices have been created with small global shutter, with high performance and low production costs. As the technology advances, IR QD technology will become even more accessible and bring SWIR sensing capability into the mass market.

Hao Pang is the CEO and founder of Quantum Science, Daresbury, U.K.; https://quantumscis.com.

Multiphoton effect exists within quantum interference of light

Researchers in Germany and Scotland explore how the visibility of the Hong-Ou-Mandel effect is affected by contamination and disprove an assumption that multiphoton components only impair visibility.

SALLY COLE JOHNSON, SENIOR TECHNICAL EDITOR

A team of researchers from Leibniz University Hannover (Germany) and the University of Strathclyde (Scotland) recently experimentally proved the interference effect between thermal light and parametric single photons also leads to quantum interference with the background field—which means the background field can't simply be ignored and subtracted from calculations, as was previously believed to be the case.

They originally set out to explore the Hong-Ou-Mandel (HOM) effect within the frequency domain between two imperfect single-photon states from a parametric down-conversion source.

"Our first results motived us to further explore this effect and how it is affected by different photon statistics, such as a thermal field and a heralded single-photon state," says Professor Michael Kues, head of the Institute of Photonics at Leibniz University Hannover.

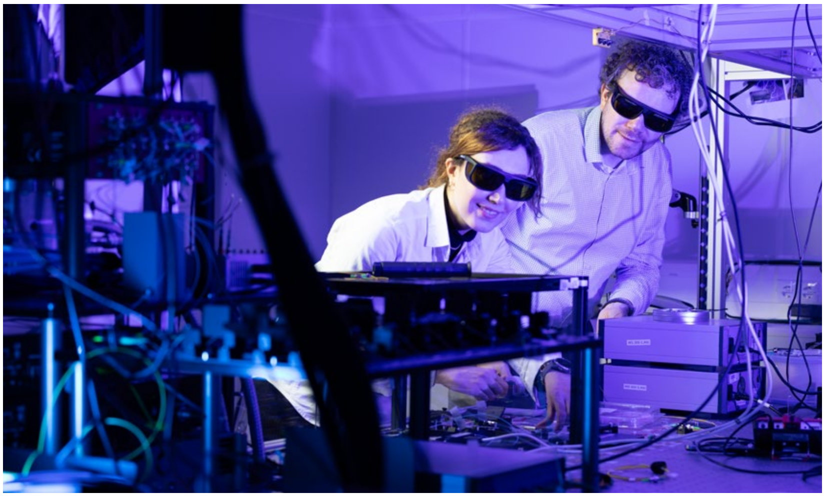


FIGURE 1. Anahita Khodadad Kashi and Michael Kues at the Institute of Photonics performing the quantum experiment. *(Image credits: IOP)*

Hong-Ou-Mandel (HOM) effect

What exactly is the HOM effect? "The HOM effect is an exclusively nonclassical phenomena, discovered in 1987," explains Anahita Khodadad Kashi, a Ph.D. student who works with Kues on photonic quantum information processing research at the Institute of Photonics (see Fig. 1). "It's a two-photon quantum interference effect with no classical counterpart. Since its discovery, the HOM effect has found applications within quantum technology research."

One concrete example of its application is for measurement-device-independent quantum key distribution (MDI-QKD), an infosec field with potential to revolutionize the current communication methods and usher in the era of the quantum internet. Another significant application of the HOM effect is for quantum metrology, which enable an unprecedented measurement resolution by preparing N00N states (a quantum mechanical many-body entangled state).

"The HOM effect is widely implemented in spatial degrees of freedom requiring a balanced beam splitter, and it's been studied for different photon statistics as input fields," says Khodadad Kashi. "We explored this effect between a thermal field and a heralded single-photon state, and surprisingly discovered that multiphoton events also contribute to

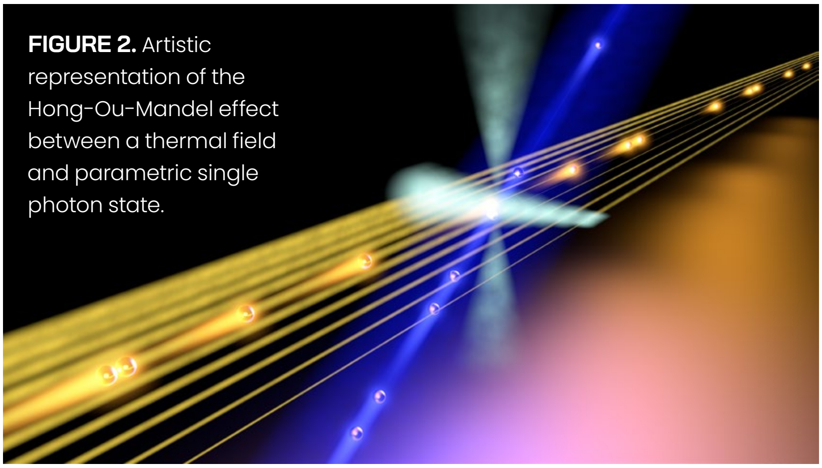


FIGURE 2. Artistic representation of the Hong-Ou-Mandel effect between a thermal field and parametric single photon state.

improving the visibility (engage in the quantum interference)."

They turned to electro-optic phase modulation to probe the HOM effect in the frequency degree-of-freedom between a thermal field and a heralded single-photon state (see Fig. 2). "We used a programmable wavelength-selective switch as a standard telecommunication component for our system, as well as a pulsed laser source and a periodically poled lithium niobate waveguide," says Kues. "And we used superconducting nanowire single-photon detectors (SNSPD) at the detecting stage."

An important aspect of the team's experimental setup was its reconfigurability, which enables its integration into the scalable future quantum networks.

Multiphoton components

When the team explored how the visibility of the HOM effect is affected by multiphoton contamination, "we disproved an assumption that multiphoton components would only impair visibility and can therefore be subtracted in the calculation," says Khodadad Kashi.

This new fundamental characteristic "wasn't considered in previous calculations," says Khodadad Kashi. "Our newly developed model can predict the quantum interference and we can measure this effect in an experiment."

Intriguingly, the team's work reveals a contributing role for the multiphoton components in imperfect parametric single-photon sources, which are widely deployed. "For quantum networks, there was a firm common belief among researchers in terms of considering a mere degradative role for the multiphoton components," says Kues. "But our experimental discovery accompanied with our novel theoretical model proves otherwise—and it has potential implications for the security of communications in MDI-QKD."

Before arriving at their final conclusions and discovery, the team faced challenges interpreting their experimental results. "When we applied the common method for retrieving the HOM visibility, we got a physically impossible result," says Khodadad Kashi. "It motivated us to look into this in more detail. With a new model, we were able to explain the experimental results—demonstrating that multiphoton components engage positively in the visibility."

Their a-ha! moment really hit when they were able to explain the observed phenomena by a theoretical model they derived—it clearly explains the source of additional contribution to the visibility (it comes from the interference of the thermal parts of the fields). "At this point, we knew we'd come to a nontrivial discovery within the field," she adds.

One current challenge within the quantum research realm "is the application of imperfect single-photon sources such as a heralded state from a spontaneous parametric down-conversion process," says Kues. "Such an approximation of single-photon states is unavoidably accompanied by multiphoton contaminations, which can cause security gaps as quantum interference of different states of light is considered. In our work, we gave prominence to the role that multiphoton components can play in improving HOM visibility. This aspect needs to be considered when interpreting HOM visibility as a measure for secure communications."

Quantum researcher Lucia Caspani at the University of Strathclyde was the first to test out the team's new approach—and it helps provide a better understanding of quantum phenomena.

MDI-QKD

The most likely application of the team's work is MDI-QKD, where the security of key establishment between legitimate end users relies on precise interpretation of the HOM effect and sources that contribute to HOM visibility. "Enabling highly secure QKD brings us one step closer to a future vision for the era of the quantum internet," says Khodadad Kashi.

What's next? "To study this effect in higher-order quantum interference systems," says Kues.

FURTHER READING

A. Khodadad Kashi, L. Caspani, and M. Kues, *Phys. Rev. Lett.*, 131, 233601 (Dec. 4, 2023); doi:10.1103/physrevlett.131.233601.

Theoretical model makes qubits 'fly'

University of Konstanz physicists in Germany create a theoretical model of how an exchange of information between qubits could work by using photons to transport quantum information—and the qubit's information content (electron spin state) gets converted into a flying qubit.

SALLY COLE JOHNSON, SENIOR TECHNICAL EDITOR

While researchers around the globe race to turn quantum computers into reality, it's no small quest because the basic components of such a computer, quantum bits or qubits, are extremely fragile. In fact, it's challenging to keep such a fragile system intact and even more difficult to interconnect qubits.

This prompted Benedikt Tissot, a physics Ph.D. student, and Guido Burkard, a professor of condensed-matter theory and quantum information in the physics department at the University of Konstanz, to ask the question: How can a stable exchange of information between qubits be achieved?

Their solution—based purely on theory work—is flying qubits (photons). Tissot and Burkard created a theoretical model of how the information exchange between qubits could work by using photons as a means of transport for quantum information.

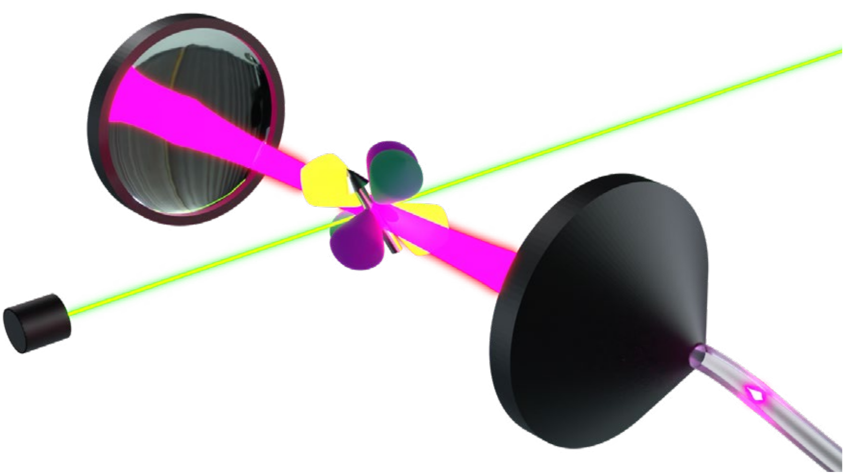


Illustration of a quantum system (silver arrow and yellow, green, and purple orbitals) interacting with a resonator (two mirrors and pink light field between them). The quantum system is controlled by a control field (green laser). A photon (pink luminous drop) is emitted into an optical fiber through one of the mirrors. *(Image credits: Benedikt Tissot)*

The basic premise behind their work is that the information content (electron spin state) of the material qubit can be converted into a flying qubit.

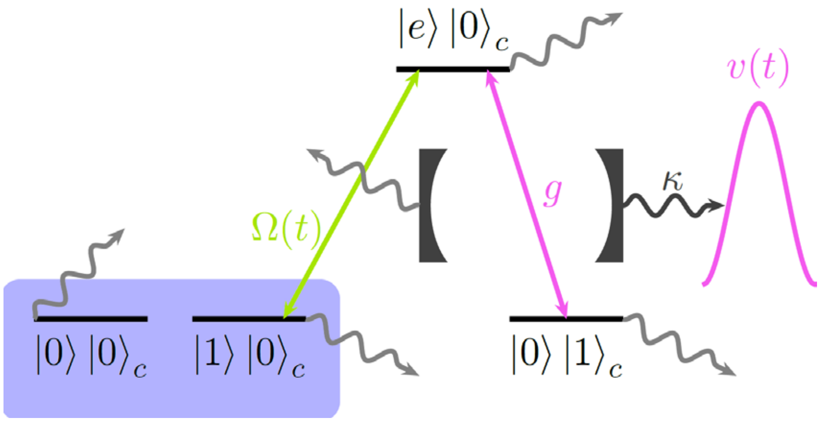
Photons are light quanta and make up the basic building blocks of the electromagnetic radiation field. A special feature of the researchers' model is that it taps stimulated Raman emissions to convert qubits into photons—and it enables more control over the photons.

Flying qubits

This approach is a "paradigm shift from optimizing the control during the generation of the photon to directly optimizing the temporal shape of the light pulse in the flying qubit," says Burkard.

Their inspiration "comes from the analogue to the classical internet, to transmit information over longer distances one option is light propagating within an optical fiber," says Tissot. "If we now think about quantum information and encode our states within quantum states, one option is the quanta of light—a.k.a. photons."

The principle of information exchange between qubits in a quantum computer works in a similar way. Information must be converted into states that are easy to transmit—and photons are an ideal way to do it.



The stationary qubit (blue background) state is emitted via a matter excited state |e> and a cavity excitation |1>_c into a flying qubit pulse. The flying qubits' temporal shape v(t) is controlled via the time-dependent drive Ω(t) and at best balances the finite coherent couplings g and κ against unwanted losses (light gray snake arrows). Note: In the matter states, the flying qubit state is omitted and the second ket describes the cavity, while the first ket describes the emitter.

Fundamentally, the researchers combine the idea of photon shaping, which is already used for single-photon sources, with quantum state transfer. "A simplified picture to contrast this would be that in the first case you would only emit one state '|1>' and in the latter you can emit superpositions of '|0>' and '|1>,'" explains Tissot.

> The method could be used for quantum state transfers between modules of a modular quantum architecture.

Superposition is an essential principle of quantum mechanics and means a quantum system is in multiple states at the same time until it's measured—think Schrödinger's cat.

Beyond this, "we account for loss processes that can destroy the quantum state of the matter system we emit from, so that our approach enables optimizing the pulse shape of the photon to balance between detrimental effects of fast varying pulses and these loss processes," Tissot says.

Theory work

The physicists focused on controlling the direction of information flow, as well as when, how quickly, and where it flows to—with a high level of control.

"The main ingredients are the matter system that needs the appropriate level structure— including the transition emitting the photon, such as defects in semiconductors like the silicon vacancy in diamond, a drive, a laser, and a cavity," says Tissot. "And the cavity enables emitting the photon in a particular direction of fiber, and the drive can be used to control the pulse shape."

Their method enables control via resonator-enhanced stimulated Raman emissions—and while it's an established method in physics, it's quite unusual to use them to send qubit states directly. But this may make it possible to balance environmental perturbations and unwanted side effects of rapid changes within the temporal shape of the light pulse, which could make information transport more accurate.

"The way we quantify the balance between different detrimental effects to optimize the pulse shape, which by design gives direct access to the pulse shape, can account for different constraints on the resulting pulse shape," says Tissot. "Furthermore, the approach to generate entanglement between the matter system and the photon uses an ancillary matter state or qubit."

A cool discovery along the way was "that the combination of accounting for losses with the pulse shaping approach leads to equations that can be straightforwardly reformulated into an optimization problem—maybe not very surprising, but cool," says Tissot.

And a couple of surprising moments involved "finding these photon shape-dependent results reproducing the (photon shape-independent) photonic memory limit for perfect emitters and slowly varying pulses as well as what we call temporal mode matching," Tissot adds.

One of the biggest challenges involved in this work was "actually—approximately—solving the dynamics and simplifying the results to be understandable," says Tissot.

As far as potential future applications, Tissot envisions their method being used for remote entanglement generation or quantum state transfers between modules of a modular quantum architecture.

Next up? "Hopefully someone will implement our approach in the lab," says Tissot.

FURTHER READING

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Encoding quantum information in states of light

How can photonics light the way and play a key role in quantum computing?

NATHANAËL COTTET

Quantum computers might have revolutionized society by now, but there's a snag: errors. Classical computers have errors, but they occur much less often and they're relatively easy to correct. In stark contrast, quantum information is exceedingly fragile. And worse, errors come in two forms: bit flips and phase flips.

Only bit flips occur in classical computers and can be easily dealt with by redundancy, using many copies of each bit to take majority votes from time to time. Quantum errors can also be solved by repeating the information across several physical qubits. But if you need 30 physical qubits to deal with bit-flip errors and 30 for phase-flip errors, you end up with nearly 1000 physical qubits to make just one error-free logical qubit (see Fig. 1). That's a typical figure for standard quantum architectures using transmons (superconducting charge qubit less sensitive to charge noise) and surface codes for error correction.

It makes for a hefty hardware overhead. And it only works if the fidelity of the physical qubits is good enough, which puts a huge burden on fidelity. So, this is the obstacle: an acute physical problem that error correction alone can at best turn into a massive engineering problem. What to do?

Photonics can light the way

Many physical platforms are currently competing to make quantum computing a reality. Indeed, many different quantum systems can play the role of the qubit, each with its own strengths and weaknesses. Think of trapped ions, neutral atoms, superconducting circuits, and even photons. Yes, light itself can be used to encode quantum information.

Optical photons bring together many advantages for quantum computing. They are easily produced and can be routed in optical fibers, propagating over long distances

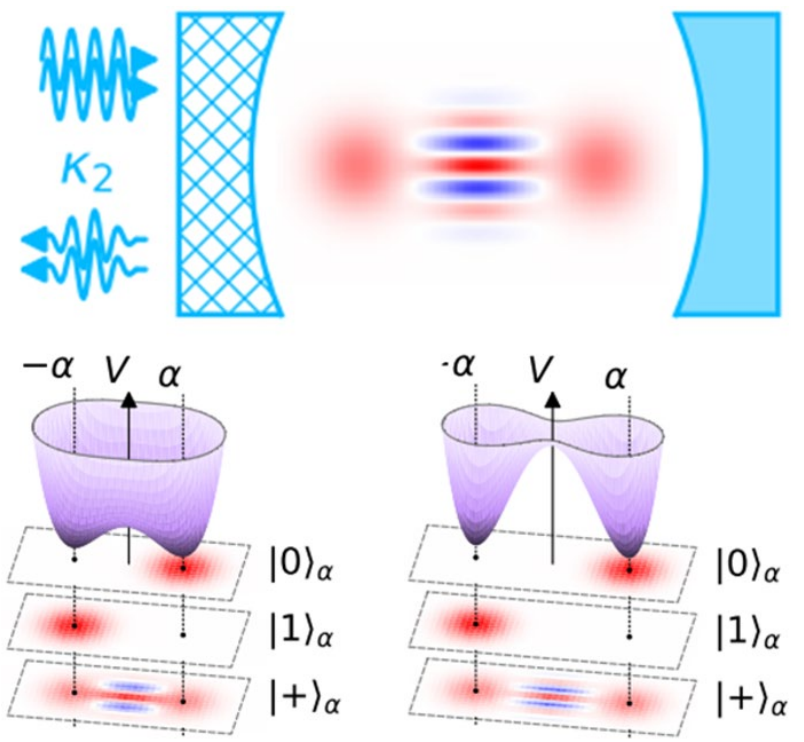

FIGURE 1. Top: Resonator (blue mirrors) exchanging photon pairs (arrows). Bottom: Increasing separation of phase space (purple) exponentially suppresses bit-flip errors that randomly swap 0 and 1. *(Image credits: Alice & Bob)*

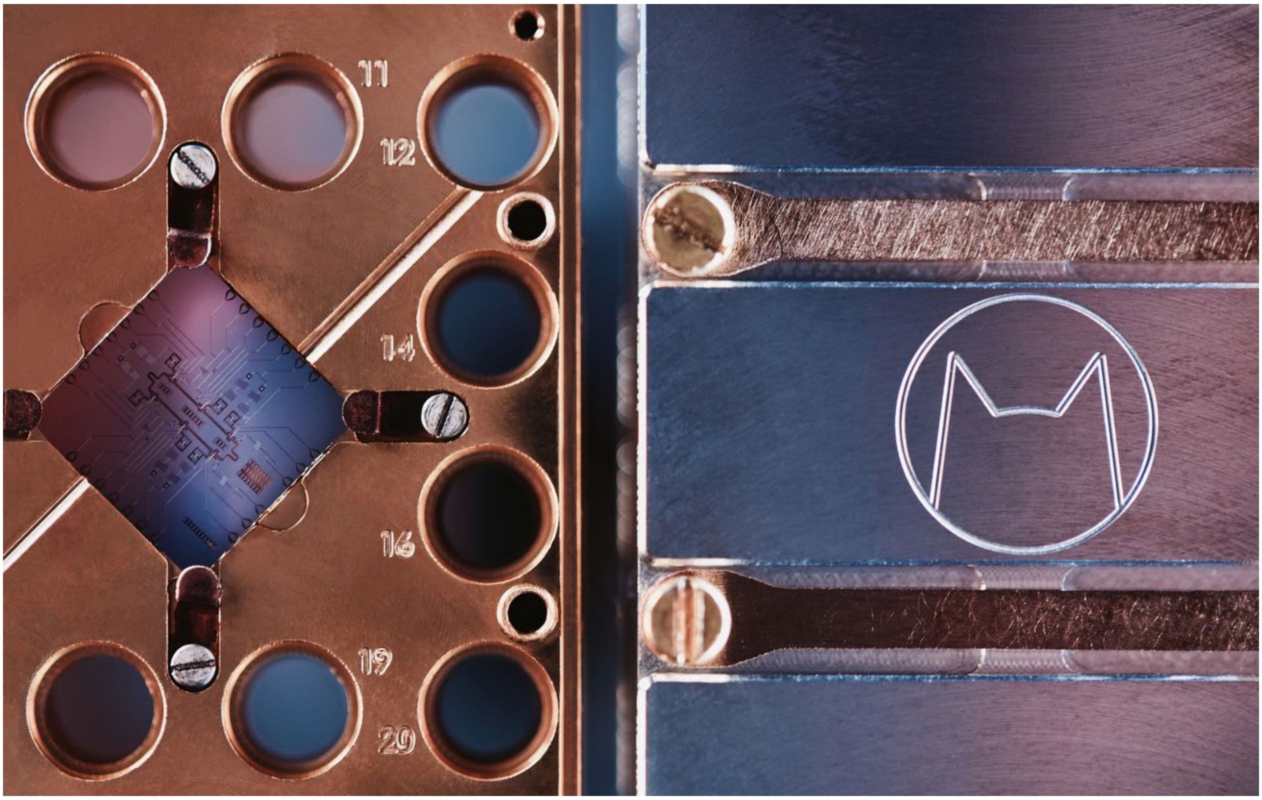

FIGURE 2. Alice & Bob's chip uses superconducting circuits to generate, stabilize, and control cat qubits.

and remaining coherent for long times at room temperature, which means they don't require expensive cryostats. Companies like Xanadu in Canada or Quandela in France have developed promising approaches to photonic quantum computing. All in all, it's a great platform for scaling, but it's much harder to run operations between qubits and program the quantum computer. This makes it more difficult to build all the necessary gate operations to achieve universality.

But it isn't the only way optics can provide a key tool in the operation of a quantum computer. Other platforms rely heavily on optics to control and measure quantum systems. Lasers are used to read out the states of trapped ions, optical tweezers to manipulate the states of neutral atoms, and microwave photons to control superconducting circuits.

There are even state-of-the-art approaches to quantum computing where ideas from quantum optics provide more than just a tool—and provide a method that directly addresses the biggest problem in quantum information.

The cat qubit

The idea here is to attack the error problem head on: Schrödinger cat states are quantum superpositions of two coherent states of light that are effectively mirror images of one another.

The quantum logical "0" is a collective state of photons in which they all share the same amplitude and phase. It corresponds to the state of light created by a laser. The logical "1" is the same state except that the phase of each photon is the opposite. We take the same laser light as we did before, but delay it just as much as needed so that all photons have the opposite phase of the ones in our first beam.

Such states are often referred to as "classical" because they correspond to the usual excitations of resonators: using mirrors to trap the light of a laser in an optical cavity, the corresponding coherent state inside is described mathematically in the same way as a mass oscillating at the end of a spring.

> The idea here is to attack the error problem head on.

The laws of quantum mechanics allow us to prepare not only these two distinct coherent states, but also superpositions of them. In the laser analogy, this would correspond to the laser emitting the same photons with two different phases at the same time. These states are called Schrödinger cat states, named after the famous thought experiment in which a cat could be both dead and alive due to quantum effects. Schrödinger's aim was to show how absurd it would be if the principle of quantum superposition could be transposed to our classical world.

In the present case, no cats are harmed, but the idea is the same: we can generate and observe coherent quantum superpositions of classical states, not of cats, but of light. And the idea and first realization of these states originated in optics. Cat states of photons at microwave frequencies were then realized and French Physicist Serge Haroche was awarded a Nobel Prize in Physics in 2012 for his groundbreaking work in quantum optics.

Putting the cats to work

What's the connection with the error problem? At Alice & Bob, we use superconducting circuits to generate, stabilize, and control qubits based on Schrödinger cat states. Cat states are interesting quantum objects that can teach us a lot about the fundamentals of quantum mechanics, but our goal is to create practical quantum computers. And it turns out cat qubits have one particular property that makes them eminently suitable for fault-tolerant quantum computing: a built-in ability to resist bit-flip errors.

For a cat qubit, a bit flip corresponds to flipping the phase of all the photons making up the coherent state. The more photons, or the stronger the laser intensity in the previous analogy, the more difficult it is for the environment to flip these phases. In fact, bit-flip suppression rises exponentially with the number of photons contained in the coherent state.

In a recent experiment, we demonstrated a six order of magnitude increase in the bit-flip time of our cat qubit, from a few microseconds to more than 10 seconds![1]

This means a quantum computer based on cat qubits wouldn't have to worry about bit-flip errors. It remains only to correct for one kind of error: phase flips. Our error correction code is therefore greatly simplified, and we expect to build logical qubits out of cat qubits much earlier, resulting in fault-tolerant quantum computers using 60 times fewer resources than the current state of the art, as demonstrated in a recent simulation of the overhead required to carry out Shor's famous algorithm to factorize large numbers.[2]

> We use superconducting circuits to generate, stabilize, and control qubits based on Schrödinger cat states.

Taming Schrödinger's cats

The cat qubits (see Fig. 2) we engineer at Alice & Bob are made of photons, but not the ones you can see. They're in the microwave range, with wavelengths about 100,000 times longer than visible photons and close to telecom frequencies. These photons are not produced by lasers, but rather by microwave sources. And they don't propagate in optical fibers, but in coaxial cables. Instead of measuring them with photodiodes, we digitize their electromagnetic waves.

Temperature is even more important. If we tried to encode quantum information in the state of a few microwave photons in a quantum memory at room temperature, it would be overwhelmed by the hundreds of thermal photons generated in the equipment itself. To avoid this problem, our memories are cooled down to 10 millikelvin, close to absolute zero, in specially designed cryostats (see Fig. 3), where the average number of thermal photons is approximately zero.

There are various ways to make a quantum memory that can trap microwave photons. They all rely on superconducting materials, which can conduct electrical current without loss, which is another reason to lower the temperature.

So how do we do this? Like most quantum states, cat states are fragile and require stabilization. Once prepared in a quantum memory, they would inexorably collapse into the vacuum by gradual loss of photons. But this collapse can be prevented by forcing the memory to gain and lose photons in pairs rather than one by one—a process called two-photon dissipation. We engineer this unusual property by coupling a second electromagnetic mode to the memory. Unlike the memory, this "buffer" is designed to lose its photons very quickly within this environment. We then implement a 2-to-1 photon exchange process between the memory and the buffer.

When the buffer frequency is half the memory frequency, this process is equivalent to second harmonic generation, or frequency doubling, well known in optics. The difference is that we can do it off-resonantly using a pump. We end up in a situation where pairs of memory photons are converted into buffer photons and then quickly lost. Going the other way, a drive on the buffer is converted into a two-photon drive on the memory, which makes the cat states stable.

Building quantum computers

Of course, if we want to process quantum information, we must apply logical operations, or gates, to our qubits. Single-qubit gates are obtained by driving the cat with a single-photon drive from a microwave source which is the equivalent of a microwave-frequency laser. The two-qubit gate needed to perform quantum error correction is the controlled-NOT (CNOT) gate. This flips the state of a target cat precisely when the state of a control qubit allows it.

To implement the CNOT gate, we engineer another well-known optical effect: an optomechanical interaction. In optomechanical systems, the radiation pressure of photons contained within an optical cavity displaces a mirror attached to a spring, thereby forming a resonator. This interaction is not native to superconducting circuits but, like the two-photon dissipation, is engineered using parametric processes.

This account demonstrates that the crucial features of cat qubit technology rely on our ability to perform nonlinear optical operations. How is this done for microwave photons? In fact, we use Josephson junctions, nanoscale elements made of a layer of insulator sandwiched between two superconductors. By building superconducting circuits containing Josephson junctions, we can design the desired interactions between the components of our system.

This is rather like what happens in nonlinear optics when a nonlinear crystal is inserted in an optical cavity. But an important difference with optics is that the interaction between microwave photons and Josephson junctions can be made more than a hundred times stronger than the typical interaction between optical photons and crystals. This means the nonlinear effects engineered in superconducting circuits are likewise stronger.

Only a few years ago, it looked like building an error-protected quantum computer might be an impossible feat. It's certainly one of today's major technological challenges, but we're getting closer to it every day at an increasing rate—thanks to technologies like cat qubits, which benefit greatly from the field of photonics.

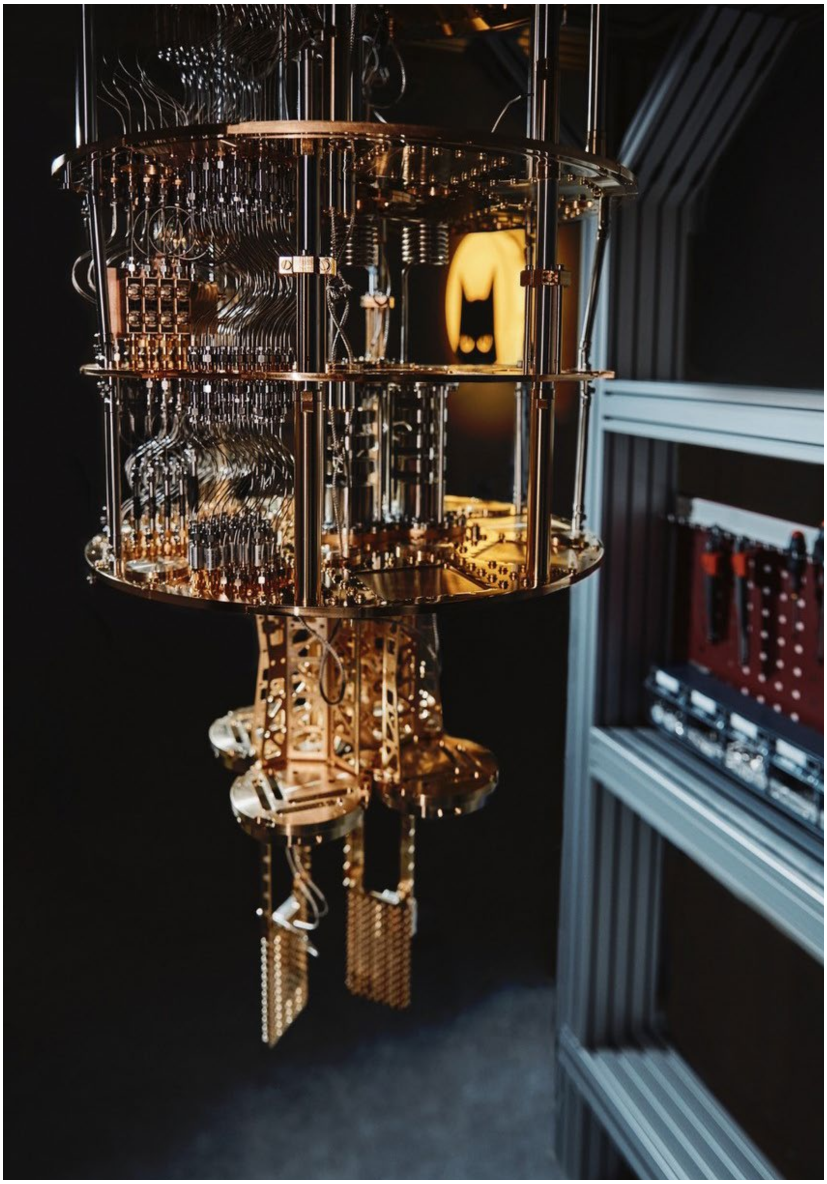

FIGURE 3. Alice & Bob's cryostat cools quantum memories down to 10 millikelvin.

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Polaritonic nanocavities redefine limits of light confinement

A team of researchers in Israel and Spain create a new type of light confinement—and open the door to new quantum electrodynamics experiments.

SALLY COLE JOHNSON, SENIOR TECHNICAL EDITOR

In a quantum nanophotonics breakthrough, a new type of polaritonic nanocavities is redefining the limits of light confinement. A team of physicists from Bar-Ilan University in Israel and the Institute for Photonic Sciences (ICFO) in Spain created nanocavities with a subwavelength volume (smaller than 100 × 100 nm^2 in area and merely 3 nm thick), which can confine light for significantly longer durations than previously possible.

The team's work provides a new solution in a long-standing quest to find ways to cram photons into increasingly small volumes. When a photon gets crammed into a cavity much smaller than a wavelength, it effectively becomes more concentrated, which enhances interactions with electrons and amplifies quantum processes within the cavity.

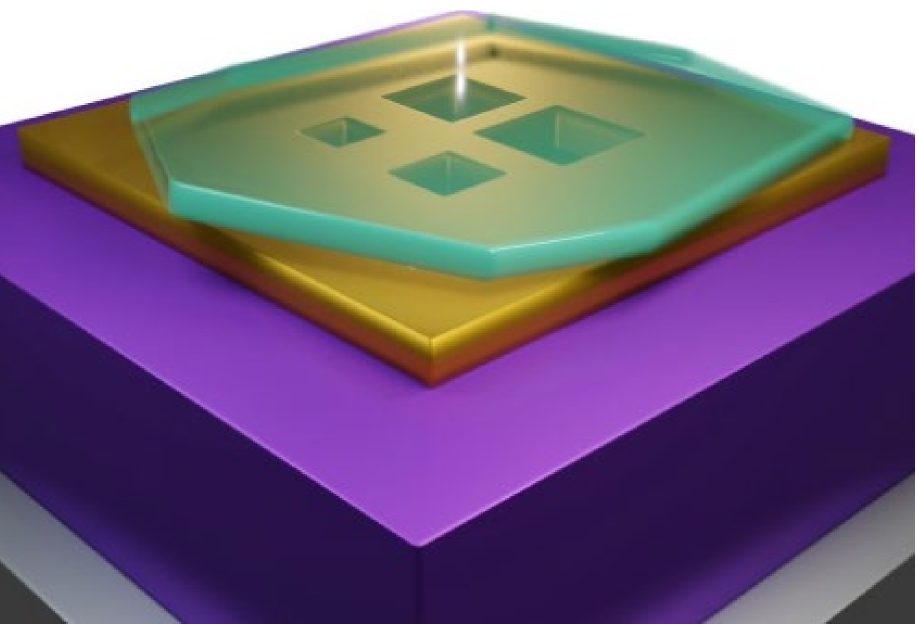
"This all started as an accidental observation," says Hanan Herzig Sheinfux, an assistant professor at Bar-Ilan University, who was at the time working Professor Frank Koppens at ICFO. "We were working on a completely different project, routinely using nearfield optical microscopy as a characterization tool to see if some process was working or not. I was actually going over the results of one of the routine characterization scans when I noticed something odd."

This "hmmm...that's weird" moment was triggered by seeing a stronger-than-anticipated reflection at one of the interfaces, which made Herzig Sheinfux wonder if it could lead to something useful.

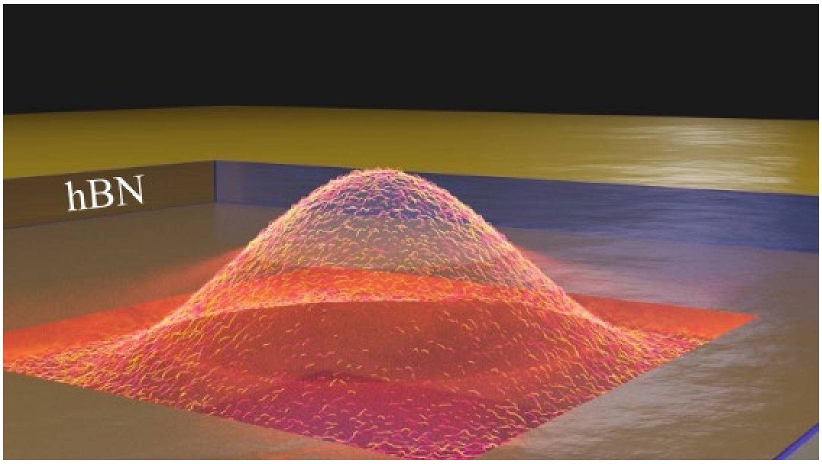
As a side project, the team decided to recreate these strong reflections, combine several reflections, and confine the light within a small volume. "We didn't expect to see much at first," Herzig Sheinfux says. "I was expecting to get some preliminary indication the idea works and maybe pass the work to a young Ph.D. student as a nice and simple project."

But the results indicated the reflections were much stronger than anticipated, and the photon confinement was far better than anticipated as well.

"Our results are opening the door to new quantum electrodynamics



Three-dimensional rendering of four polaritonic cavities of different sizes. *(Image credit: Matteo Ceccanti)*



Artist's impression of a nanocavity and the field inside it.
(Image credit: Matteo Ceccanti)

experiments, exploiting the power of 'weird' concepts like vacuum fluctuations," says Herzig Sheinfux. "These experiments and this work can have some practical applications, but the physics involved is astoundingly beautiful. There's some very deep and thought-provoking concepts hidden within what seems to be the relatively simple cavity designs. It's like a work of art—except it's made by nature, not Mozart or Picasso."

New polaritonic nanocavity confinement technique

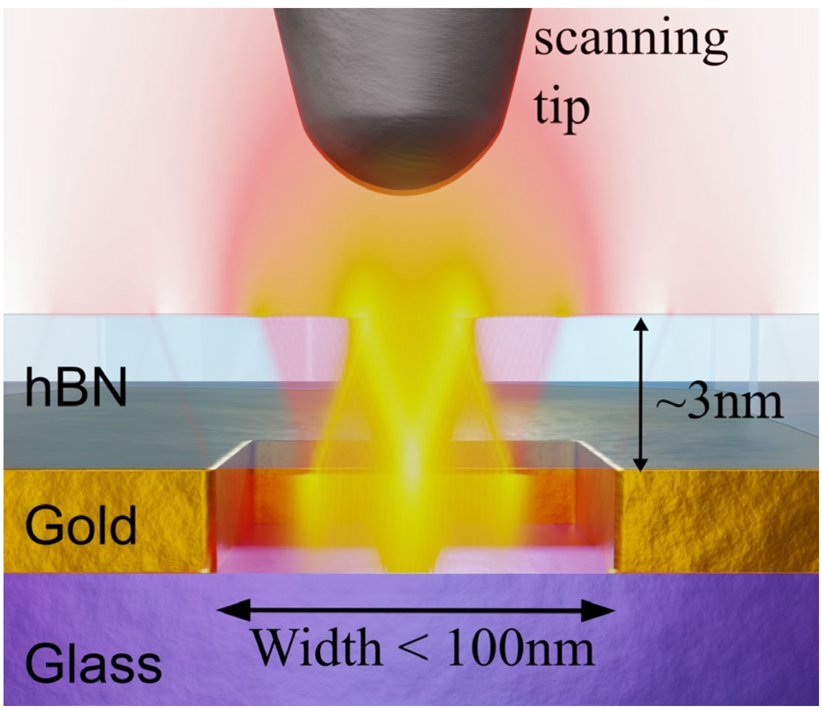
The team's technique taps an exotic form of light: hyperbolic-phonon-polaritons. Hyperbolic-phonon-polaritons are electromagnetic excitations that occur within the two-dimensional (2D) hexagonal boron nitride (hBN) material, a.k.a. white graphene, which forms the cavity. And it uses a new and indirect confinement mechanism: nanocavities are created by drilling nanoscale holes into a gold substrate with the 2- to 3-nm precision of a helium-focused ion beam microscope.

After the holes are drilled, hBN flakes are placed atop these nanometric holes within a gold substate to support electromagnetic excitations (the hyperbolic-photon polaritons). "It's a lot more complicated than it sounds," Herzig Sheinfux says. "For example, the holes in the gold must be exceptionally precise—10 to 20 atoms in the wrong place would spoil the response of the cavity completely."

Essentially, cavities are created by changing the environment of the polaritons as they travel through a flake of hBN. "A sharp change of this environment implies a sharp change in polaritonic behavior, which causes the polaritons clog up and be confined within a small area," says Herzig Sheinfux. "Think of it as roughly akin to a traffic jam that begins because of car congestion when a two-lane expressway is reduced to a one-lane expressway."

Hyperbolic-photon polaritons can be confined to extremely small volumes. When polaritons pass above the edge of the metal, they catch a strong reflection—and get confined. The team's approach avoids shaping hBN directly to preserve its pristine quality and enable highly confined and low absorption photons within the cavity.

The biggest obstacle in their work—and the origin of the team's second discovery—occurred when Herzig Sheinfux realized the cavities weren't



Sketch of a nanocavity (cross-section view) and the nearfield tip, superimposed with the simulated ray-like field distribution of the cavity modes.
(Image credit: Matteo Ceccanti)

merely responding really strongly, they were in fact responding more strongly than should be possible. “Based on the theory we started with, the cavities were supposed to function half as well as they actually did,” he says. “This stumped us because experiments don’t normally outperform theory, and because all of the theoretical explanations we had didn’t make sense.”

They eventually puzzled out that the high-performance level of these cavities is actually related to intricate multimodal interference effects, which are extremely complex. “It involved lots of hard work to get to this point, and a lot of explanations that looked promising ended up making no sense,” says Herzig Sheinfux.

Once the team found their working hypothesis, everything clicked into place. “It was satisfying to find this elegant solution—and it’s the type of experience that made me certain I wanted to become a physicist in the first place,” Herzig Sheinfux adds.

The high-performance level of these cavities is actually related to intricate multimodal interference effects, which are extremely complex.

Harness quantum fluctuations within nanocavities?

Nanocavities are used in physics to enhance light-matter interactions. But previous generations of nanocavities were plagued by significant amounts of absorption, which prevented some of the most exotic quantum electrodynamics from being achieved.

“With our new hypercavities as a platform, we hope to be able to harness quantum fluctuations that occur within empty cavities,” says Herzig Sheinfux. “There’s no real vacuum within our quantum universe—there’s some energy even inside what’s supposed to be an empty box and we hope to observe the fluctuations induced by this energy, to measure their effects, and maybe to use them to enhance various processes. Finding a way to do it is a challenging task, but it’s the top priority for us now.”

FURTHER READING

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Is your Quantum 2.0 solution stable enough?

Quantum 2.0 technologies—including computing, imaging, sensors, timing, communications, and more—will require much tighter control of light.

SCOTT DAVIS, KEVIN KNABE, ANDREW ATTAR, AND MARK WIPPICH

Vescent, a provider of Quantum 2.0 technologies which enable commercialization of deployable devices that have, up until now, struggled to escape the lab and live up to their potential, has developed a range of new products to provide the latest in low size, weight, and power (SWaP), ruggedness, and performance for quantum applications. This includes frequency combs (see Fig. 1), lasers, and controls (see Fig. 2) for quantum timing (optical clocks), computing, networking, and sensing.

All Quantum 2.0 technologies leverage a decades-long effort by physicists across the globe to gain tighter control of light and light-matter interactions.

During Quantum 1.0, the invention of the laser gave us dramatically improved control of light—its wavelength (or frequency), directionality, and phase coherence—in ways that revolutionized the world from medicine to communications to manufacturing.

Now, Quantum 2.0 demands even tighter and more nuanced control of light than ever before. In the case of emerging applications that exploit the quantum behavior of atoms, ions, or molecules, light is the tool of choice to coax the desired behavior from these quantum entities.

FIGURE 1. Vescent's team in the cleanroom assembling frequency combs. *(Photo credits: Vescent)*

FIGURE 2. Frequency combs and controls ready to ship to customers.

The amplitude, phase, and frequency of light are the degrees of freedom used to elicit a specific action. But how much tighter control over these degrees of freedom is really required for Quantum 2.0? In terms of relative accuracy, the frequency of the light has the most stringent requirements: an error of just 1 in 10 trillion (1×10^{-13}) is often enough to render the light completely useless to the quantum operation (see Fig. 3).

It's difficult but important, and Vescent is working with the quantum community to achieve it.

To support this mission of achieving real-world quantum applications, Vescent is shrinking and ruggedizing frequency-stabilized laser modules. The initial products that are transforming the capabilities of deployed quantum systems are modular frequency combs (see Fig. 4) that have been shown to operate within a clock setup from -10° to 60°C and within the presence of >1g RMS vibrations—harsher environments than any quantum laser control systems have been shown to operate to date.

These optical frequency combs are laser systems that inherently connect the optical and microwave domains and will support a variety of applications, including optical atomic clocks for improved timing and navigation, quantum computing for laser frequency control, and a host of quantum sensors to detect accelerations, rotations, and electromagnetic fields with precision and accuracy beyond the limits of their classical counterparts.

To support this mission of achieving real-world quantum applications, Vescent is shrinking and ruggedizing frequency-stabilized laser modules.

Vescent has miniaturized and ruggedized a host of continuous-wave lasers and their control electronics for pumping and probing atoms. These sources can work on their own or be integrated with optical frequency comb technology.

For example, quantum systems often require reliable relative frequency stability at the 10^{-14} level. Systems such as quantum computers need to discipline multiple laser frequencies against a master laser that simply put: "just doesn't move." Traditional approaches to this problem, such as vacuum-enclosed ultralow-expansion glass high-finesse cavities, can provide short-term stability, but longer-term drift can limit operation uptime.

To address this problem, Vescent is now shipping tools such as a robust optical frequency comb and an acetylene-stabilized laser (the Stabilaser from DFM). This kit enables users to control the frequency of their light source with a relative stability down to a few parts in 100 trillion ($<3 \times 10^{-14}$), depending on the feedback time. By exploiting the lockstep connection between the optical and microwave portions of the spectrum afforded by optical frequency combs, frequency synthesis can be accomplished from one portion of the spectrum to the other. Thus, the high stability of a source can be transferred to and from any wavelength from 500 to 2000 nm in the optical domain and to and from harmonics of the 100- or 200-MHz repetition rate of the comb up to 10 GHz.

In a recent example, a Vescent customer approached the team with a problem: their quantum application required a laser that needs to maintain both its fractional linewidth and its relative frequency stability to better than 5×10^{-14} for their quantum operations to work.

Using a state-of-the-art, ultralow-expansion (ULE) cavity-stabilized laser, they achieved the required

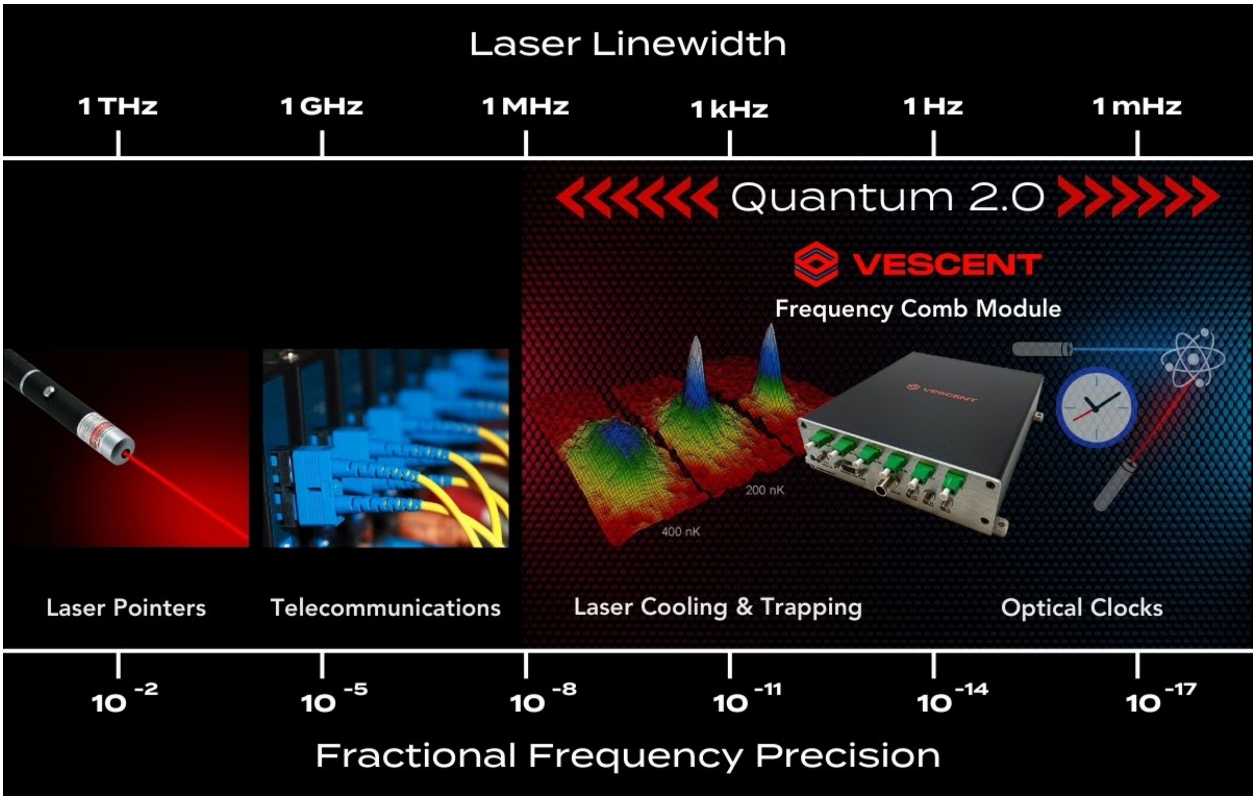


FIGURE 3. Laser linewidth and fractional frequency precision and accuracy requirements needed for Quantum 2.0, which Vescent's frequency comb module enables (red laser pointer image from Phantom Dynamics Website).

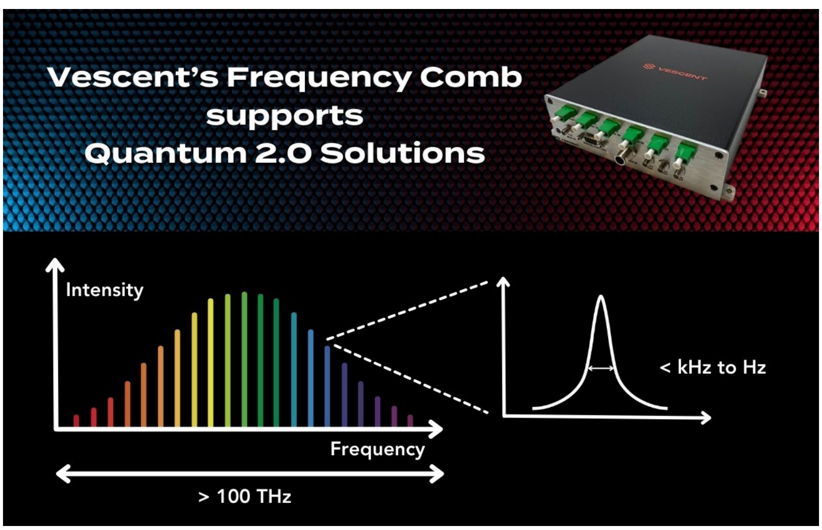


FIGURE 4. Vescent's frequency comb supports Quantum 2.0 solutions.

linewidth, but the characteristic instability of the cavity means that, due to uncontrolled drift, recalibration of the laser frequency was needed every few minutes before operations could continue.

For Quantum 2.0 to offer widespread utility out in the real world, this repeated downtime is an unacceptable barrier. To address it, Vescent developed a frequency stability kit so users can now discipline their ULE cavity-stabilized laser frequency to a relative instability of better than 5×10^{-14} for days at a time. This led to an estimated 30–300X improvement in operational uptime for the user's quantum system, dramatically improving both the utility and capabilities of their quantum application.

Vescent is in the vanguard of the Quantum 2.0 revolution in sensing by deploying quantum-based devices and methods in the field. They offer lasers, combs, and controls that have been ruggedized and have already proved their utility in the field.

Scott Davis is CEO, **Kevin Knabe** is the director of research and development, **Andrew Attar** is a staff scientist, and **Mark Wippich** is a board member and corporate development advisor, all at Vescent, Golden, CO; e-mail: media@vescent.com; https://vescent.com.

Quantum Corridor opens door to fast, secure comms in Midwest U.S.

In this Q&A with Ryan Lafler, president and chief technology officer of Quantum Corridor, he discusses the project and shares its goals and potential applications.

SALLY COLE JOHNSON, SENIOR TECHNICAL EDITOR

***Laser Focus World:* How did Quantum Corridor get its start?**

Ryan Lafler: Quantum Corridor is a public-private partnership formed in 2021 with the state of Indiana, which is enabling advanced Illinois and Indiana tech innovators to exchange data nearly instantaneously and achieve groundbreaking advances. It was funded through a $4 million grant from the state of Indiana's READI grant program, with the cooperation of the Indiana Department of Transportation and Northwest Indiana Forum.

In October 2023, a successful coherent reconfigurable line system (RLS) flexgrid transmission between the Chicago ORD 10 Data Center and the Digital Crossroads data center in Hammond, Indiana, marked a significant milestone in the network's development. This transmission achieved connectivity speeds more than 1000x faster than traditional fiber networks—paving the way for future quantum transmissions along the network once applications are integrated.

Quantum Corridor unlocks previously impossible connectivity opportunities for corporate, defense, and instructional platforms through its unprecedented combination of speed, throughput, and low latency.

It's North America's first network to achieve a capacity of 40 terabits per second (Tbps), making Quantum Corridor one of the fastest Tier-One networks on the continent. This translates to the ability to transmit 1 million photo files or 1500 hours of high-definition video every second.

The network will possess the capacity to transmit nearly the entire current content load of the internet within a single transmission at 1.2 petabits per second (Pbps). This is the equivalent to transmitting 600 billion pages of text every second.

Ryan Lafler, president and chief technology officer of Quantum Corridor. *(Photo credit: Quantum Corridor)*

And it's already achieved a latency of 0.266 milliseconds of information exchange over its current 12-mile (19.3-km) network—a transmission speed 500x faster than the blink of an eye and far exceeding the average network's latency, which is 12x longer.

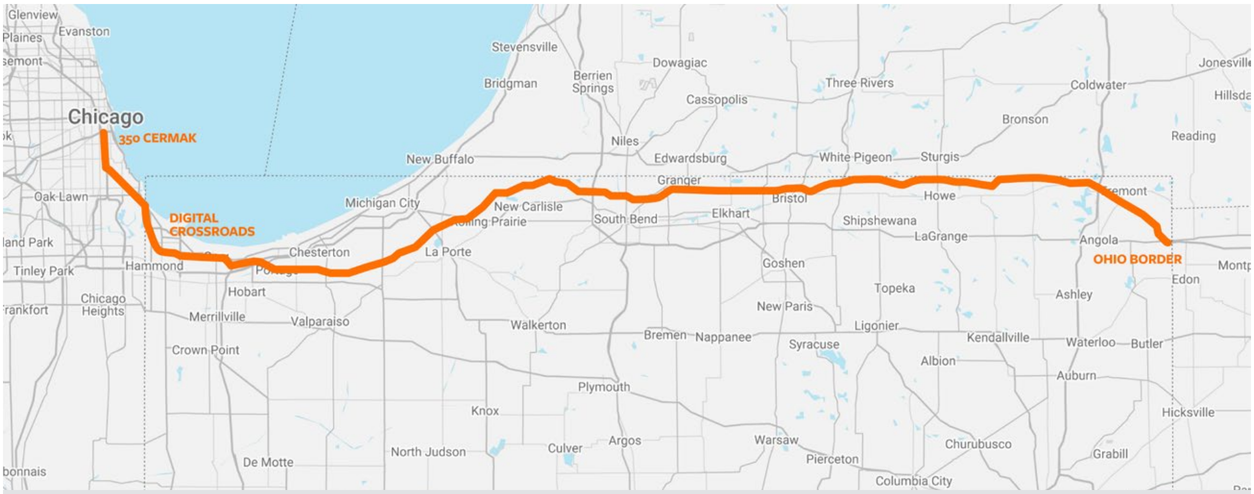
Ciena, a provider of networking systems, services, and software, and C1, an engineering and technology implementation provider, serve as key collaborators in solution design and tech implementation, respectively, in building the entire 263-mile corridor.

Quantum Corridor plans to continue expanding its network and connecting research facilities.

***LFW:* Why is the Midwest an ideal location for a quantum tech hub?**

Lafler: The Midwest is poised to become the quantum center of the U.S. because the region has many world-renowned quantum research institutions in Chicago and Indiana. It also has underutilized Department of Defense and military base assets that will be located along Quantum Corridor's fiber-optic network once it's expanded.

Beyond this, the Midwest has access to land, power, and one of the



Quantum Corridor is a 263-mile (423.2-km) stretch of new and existing fiber-optic cable that runs beneath the Indiana Toll Road to link data centers, quantum research facilities, life sciences and genome scientists, and hyperscalers from Chicago to Northwest and West Central Indiana—providing industry-shattering speeds and throughput. *(Image credit: Quantum Corridor)*

largest bodies of fresh water within North America, which is essential to support quantum infrastructure. The region's central location on the continent also makes it ideal for defense research.

LFW: **What type of fiber-optic cable is involved?**

Lafler: It's a coherent RLS flexgrid transmission, essentially the most modern variation of dense wavelength division multiplexing (DWDM). This is the foundation for quantum transmission because coherent light will be used as a checksum for truth on a quantum network. Quantum key distribution (QKD) is expected to be broadcast over this network in 2024.

LFW: **What does Quantum Corridor achieve in terms of quantum supremacy, speed, and security?**

Lafler: Quantum Corridor was built from the ground up using components made in North America. It only builds dedicated waves for dedicated customer transmissions so that no other customer data traverses a dedicated customer path at any time.

The total throughput will reach 1.2 Pbps, which is equal to 600 billion pages of text transmitted every second. Today, the collective content load of every user combined globally across the internet is 1.7 Pbps, or the equivalent of sharing 22.6 years of HD video across the internet every second. Once it reaches 1.2 Pbps, Quantum Corridor will be able to throughput the amount of data that Google processes globally each day within 17 seconds.

A coherent wave is essentially a laser wavelength that combines multiple wavelengths that would normally be sent over traditional optical networks into one large wave of light. RLS stands for reconfigurable line system, which means Quantum Corridor can easily program and reprogram the environment for multi-tenant transmission or support multiple wavelengths on one transmission—setting the foundation for quantum transmission.

This passage describes the foundation for quantum transmission, where light waves are used to convey information as a truth checksum. Quantum systems or technology can integrate with this network—and take advantage of the simultaneous transmission capabilities provided by RLS flexgrid. This foundation will eventually enable quantum transmission.

LFW: **Any big challenges ahead?**

Lafler: Quantum technology is still in its early stages of development and, as we bring it to market, researchers will discover many applications within applications that are difficult to anticipate. But we do know we're making a significant impact on the science and technology community.

LFW: **What types of applications are you testing and using the network for?**

Lafler: Quantum computing offers incredible potential for breakthroughs across applications in nearly all industries, including:

- **Climate modeling and environmental impact.** Quantum computing can enhance our ability to model and simulate complex natural systems, such as climate patterns and environmental processes. This can lead to better predictions and strategies for addressing environmental challenges and mitigating climate change.
- **Financial modeling.** Quantum computing's ability to handle large datasets and complex simulations can be beneficial in financial modeling, risk assessment, and portfolio optimization. This can result in more stable financial markets and better investment strategies.
- **Artificial intelligence (AI) and machine learning.** Quantum computing can accelerate the development of AI and machine learning algorithms. This can lead to more accurate and personalized recommendations for applications like healthcare, entertainment, and online shopping.
- **Energy efficiency.** Quantum computers have the potential to design more energy-efficient materials and processes—and contribute to reduced energy consumption and a greener future.
- **Materials science and innovation.** Quantum simulations can help discover new materials with unique properties, such as superconductors and advanced batteries. These innovations can lead to improved electronic devices and energy storage solutions.
- **Scientific discovery.** Quantum computing can aid scientists in tackling complex scientific questions, such as understanding the behavior of particles at the quantum level, to simulate chemical reactions and explore the fundamental laws of physics.

Quantum computing holds great promise for advancing science, technology, and innovation—with the potential to bring about transformative changes in various aspects of our lives. Like the .com boom, there are applications we can't even fathom across quantum computing, quantum networking, and quantum commercialization, but we've laid the infrastructure for this ingenuity.

***LFW:* What's next?**

Lafler: Quantum Corridor will expand into Northwest Indiana and West Lafayette, Indiana, to connect research institutions and data centers to begin quantum data transmission.