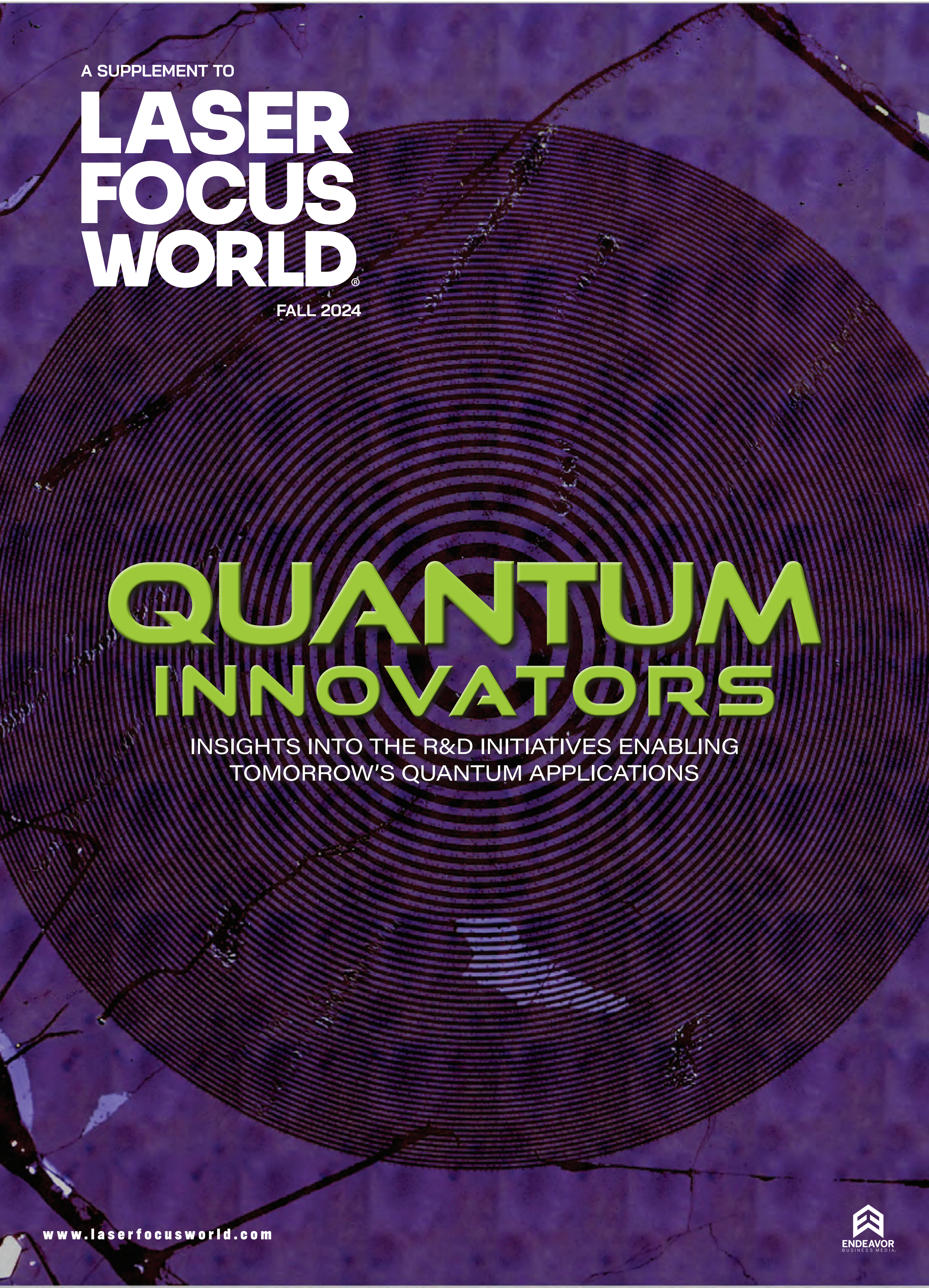
A SUPPLEMENT TO
LASER FOCUS WORLD®
FALL 2024



QUANTUM INNOVATORS

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

www.laserfocusworld.com

ENDEAVOR BUSINESS MEDIA

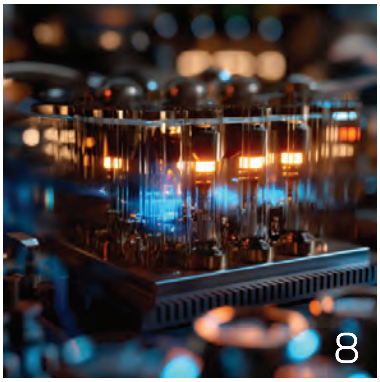
Fall 2024

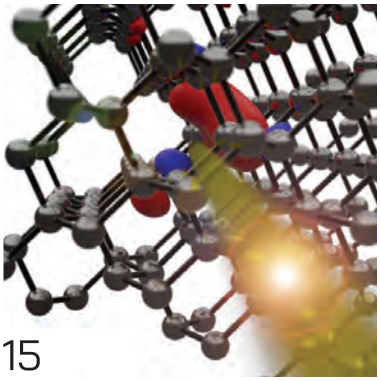
CONTENTS

ANALYST CORNER

FEATURES

QUANTUM COMPANIES TO KNOW





MARKET LEADER, DIGITAL INFRASTRUCTURE Peter Fretty
pfretty@endeavorb2b.com

EDITOR IN CHIEF Sally Cole Johnson
sallyj@endeavorb2b.com

MANAGING EDITOR Lee Dubay
ldubay@endeavorb2b.com

MULTIMEDIA DIRECTOR, DIGITAL INFRASTRUCTURE Justine Murphy
jmurphy@endeavorb2b.com

ART DIRECTOR Kelli Mylchreest

PRODUCTION MANAGER Sheila Ward

AD SERVICES MANAGER Shirley Gamboa

AUDIENCE DEVELOPMENT MANAGER Debbie Bouley

CUSTOMER MARKETING MANAGER Kevin Bennett

ENDEAVOR BUSINESS MEDIA
www.endeavorbusinessmedia.com

EDITORIAL OFFICES
Laser Focus World
61 Spit Brook Road, Suite 401
Nashua, NH 03060
(603) 891-0123
www.laserfocusworld.com

ENDEAVOR BUSINESS MEDIA, LLC

CEO Chris Ferrell

PRESIDENT June Griffin

COO Patrick Rains

CRO Paul Andrews

CHIEF DIGITAL OFFICER Jacquie Niemiec

CHIEF ADMINISTRATIVE AND LEGAL OFFICER Tracy Kane

EVP DIGITAL INFRASTRUCTURE Tracy Smith

EVP ENDEAVOR BUSINESS INTELLIGENCE
Paul Mattioli

EDITORIAL ADVISORY BOARD
Antonio Raspa, Luxinar; **Walter Burgess**, Power Technology; **Ron Gibbs**, Ron Gibbs Associates; **Jeremy Govier**, Edmund Optics; **Anthony M. Johnson**, Center for Advanced Studies in Photonics Research, University of Maryland Baltimore County; **Earl Hergert**, Hamamatsu Corp.; **Larry Marshall**, CSIRO; **Jan Melles**, Photonics Investments; **Masahiro Joe Nagasawa**, TEM Co. Ltd.; **Ralph A. Rotolante**, Vicon Infrared; **Amrita Sahu**, Altria; **Toby Strite**, IPG Photonics; **Bo Gu**, BosPhotonics; **Geoff Shannon**, Ph.D., Coherent; **Stan Ream**, SR Laser LLC; **Ronald D. Schaeffer**, PhD, PhotoMachining Inc.; **Milton S.F. Lima**, Ph.D., Instituto de Estudos Avançados; **Timothy Simpson**, Ph.D., Penn State University; **Anant Deshpande**, Persistent Systems; **Brian Victor**, nLight.

SUBSCRIPTION INQUIRIES:
Toll-free: 1-877-382-9187
International Callers: +1 847-559-7598
E-mail: LFW@Omeda.com
Web: www.laserfocusworld.com/subscribe

Laser Focus World®, USPS Permit 922380, ISSN 1043-8092 print, ISSN 2688-3589 online, is published 9 times a year by Endeavor Business Media, LLC. 201 N Main St 5th Floor, Fort Atkinson, WI 53538. Periodicals postage paid at Fort Atkinson, WI, and additional mailing offices.

Printed in the USA. Copyright 2024 Endeavor Business Media, LLC. All rights reserved. No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopies, recordings, or any information storage or retrieval system without permission from the publisher. Endeavor Business Media, LLC does not assume and hereby disclaims any liability to any person or company for any loss or damage caused by errors or omissions in the material herein, regardless of whether such errors result from negligence, accident, or any other cause whatsoever. The views and opinions in the articles herein are not to be taken as official expressions of the publishers, unless so stated. The publishers do not warrant either expressly or by implication, the factual accuracy of the articles herein, nor do they so warrant any views or opinions by the authors of said articles.

OPTICA Formerly OSA
LIA
SPIE.
Connectiv

Quantum advances and funding are flying

Plenty of mindbendy quantum advances are flying right now, and one of the coolest recent ones comes from Large Hadron Collider (LHC) experiments at CERN by the ATLAS and CMS (both detectors) teams, which observed quantum entanglement between fundamental particles known as "top quarks" *and* at the highest energies so far. Their work opens a new avenue to explore quantum physics and entanglement.

And the feds continue to crank up their support for quantum R&D within the U.S. A handful of recent investments: The National Science Foundation provided $39M to fund 23 research projects to expand access to quantum research, training, and education; the Department of Defense ponied up $32M for four quantum projects; and the Department of Energy kicked in $65M for 10 quantum computing projects (with 38 separate awards).

In this issue of *Quantum Innovators*, physicists led by Jorik van de Groep's 2D Nanophotonics group at the University of Amsterdam share their work using quantum effects to create the world's thinnest—0.6-nm-thick—flat lens. The quantum mechanical resonances of two-dimensional quantum materials inspired them to explore excitons as resonant building blocks for tunable next-gen atomically thin optoelectronic surfaces. Thank you to Ludovica Guarneri, a Ph.D. researcher working with van de Groep, for sharing her extraordinary work and the cover image with us.

Once again, we've got a wide range of everything—including market analysis articles from Eric Mounier and Doug Finke, contributed features about engineering quantum light and spin centers for quantum computing, and articles about a bunch of other amazing work—and we introduce you to three companies you should know.

Thank you to everyone who contributed or shared their cool quantum work with us!

Sally Cole Johnson
EDITOR IN CHIEF
sallyj@endeavorb2b.com

ADVERTISING SALES OFFICES

MAIN OFFICE
61 Spit Brook Road
Suite 401
Nashua, NH 03060
(603) 891-0123

Market Leader/Group Editorial Director, Digital Infrastructure
Peter Fretty
(231) 329-2739
pfretty@laserfocusworld.com

Director, List Sales
Kelli Berry
(918) 831-9782
kberry@endeavorb2b.com

NORTH AMERICA

Northeast/Mid-Atlantic/ Southeast/Eastern Canada
Tom Larranaga
(973) 460-9476
tlarranaga@laserfocusworld.com

West Coast
Renee Rubens
(917) 734-4308
rrubens@endeavorb2b.com

INTERNATIONAL

Europe
Holger Gerisch
+49-(0)8847-6986656
hgerisch@endeavorb2b.com

China/Hong Kong/Taiwan
Floyd Chun
+852 28386298; fax 852-2-838-2766
floydc@actintl.com.hk

Japan
Masaki Mori
+81-3-3219-3561
masaki.mori@ex-press.jp

FOLLOW US

Instagram/@laser.focus.world
Facebook/@LaserFocusWorld
X/@LFWmagazine
LinkedIn/Laser Focus World
YouTube/Laser Focus World

For assistance with marketing strategy or ad creation, please contact:
Marketing Solutions
Steve Porter
(785) 294-3043
sporter@endeavorb2b.com

Quantinuum eyes $10B IPO: What's its potential impact on the quantum industry?

A $10B IPO for Quantinuum may catalyze growth within the quantum sector, spur more investment, and bring quantum computing into the spotlight.

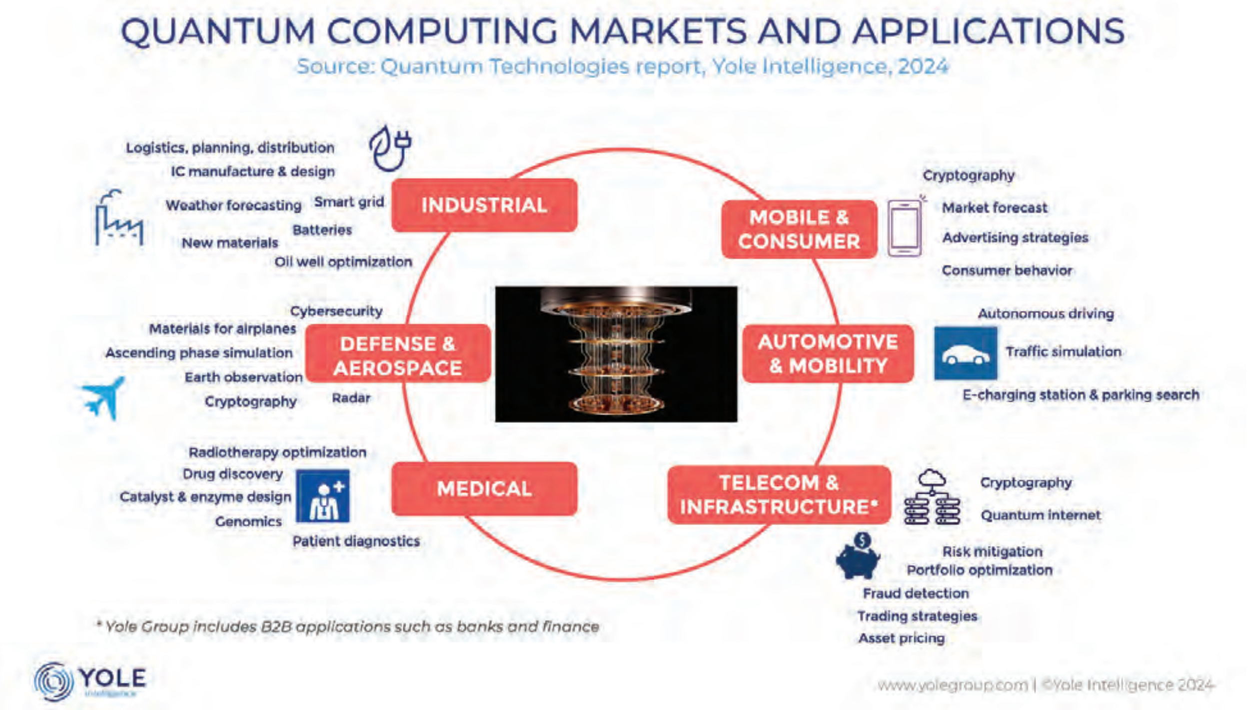
ERIC MOUNIER

Quantinuum, a leader in the quantum computing sector, is reportedly gearing up for an initial public offering (IPO) with a valuation of $10 billion. If realized, this would mark the highest valuation ever for a quantum computing company and could potentially reshape the landscape of the quantum industry.

Quantinuum has been at the forefront of quantum advancements in 2024. In January, Honeywell successfully concluded a $300 million funding round for the company, resulting in a pre-money valuation of $5 billion. This round, led by JPMorgan Chase & Co., Mitsui & Co., and Amgen Inc., brought Quantinuum's total fundraising to approximately $625 million since its inception.

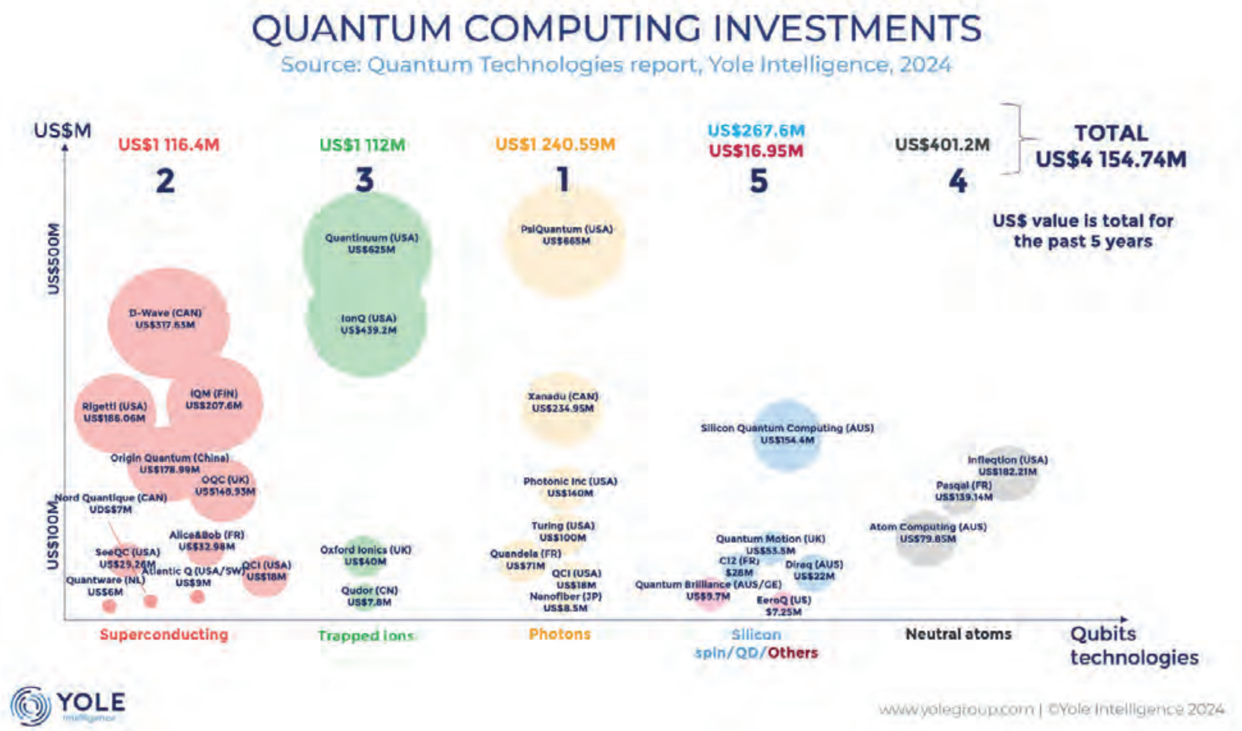
In spring 2024, Quantinuum and Microsoft achieved a major milestone by demonstrating the most reliable logical qubits ever recorded. They conducted over 14,000 error-free experiments using Quantinuum's ion-trap quantum hardware and Microsoft's qubit-virtualization system for error diagnostics and correction. This breakthrough was seen as a significant step toward moving beyond the current Noisy Intermediate-Scale Quantum (NISQ) era.

Quantinuum continued its momentum into the summer, upgrading its quantum processing unit (QPU) H2 from 32 to 56 qubits and achieving a record fidelity of 99.84% for two-qubit gates. This milestone made it the first trapped-ion-based QPU to exceed 50 qubits. While this


QUANTUM COMPUTING MARKETS AND APPLICATIONS

Source: Quantum Technologies report, Yole Intelligence, 2024

* Yole Group includes B2B applications such as banks and finance



achievement is promising, the chip's architecture, based on the 2023 racetrack design, may face challenges in scaling compared to more advanced two-dimensional (2D) architectures, which are in development by Quantinuum and other competitors like Universal Quantum, Oxford Ionics, and AQT.

Honeywell's announcement of a potential IPO valuing Quantinuum at $10 billion sent ripples through the quantum industry. Quantinuum, established in 2021 through the merger of Cambridge Quantum and Honeywell Quantum Solutions, is one of the largest full-stack quantum companies, with about 500 employees across the United States, the U.K., Germany, and Japan. Honeywell currently holds a 54% ownership stake, while Ilyas Khan, founder and chief product officer, holds 23%. Other shareholders include IBM and Japan's JSR Corp.

This would not be the first quantum company to go public, but previous IPOs have produced mixed results. Rigetti and D-Wave both went public via special-purpose acquisition companies (SPACs) in 2022 and faced challenges, including delisting risks, although they have since regained compliance. IonQ, which also uses ion-trap technology like Quantinuum, went public in 2021 and has maintained a relatively stable performance, with some fluctuations.

IPO timing

Given Quantinuum's recent achievements, the timing for an IPO could be favorable. But the process typically takes six months to a year, so the earliest we might see a Quantinuum IPO would be in early 2025.

If successful, a $10 billion valuation would position Quantinuum to significantly accelerate its research and development efforts, and potentially solidify its leadership in the quantum sector. This move could also provide a much-needed boost to the quantum industry—increasing competition and attracting more funding. Quantum computing is still a long-term bet, with technology evolving rapidly, but the road to a truly useful quantum computer remains challenging. Nonetheless, global public and private investment in quantum technologies remains strong, with over $30 billion in public and an estimated $4 billion in private investment to date, most of which was directed toward quantum computing hardware.

The potential Quantinuum IPO could further catalyze growth within the quantum sector, encouraging more investment and bringing quantum computing into the spotlight. As the quantum ecosystem matures, this IPO could mark a significant step forward in the journey toward realizing the full potential of quantum technology.

SOURCE

See www.yolegroup.com/product/report/quantum-technologies-2024.

Eric Mounier is chief analyst of Photonics & Sensing at Yole Group, Villeurbanne, France; www.yolegroup.com.

Quantum computing moves from NISQ to FTQC

While a hard demarcation between these two eras was expected by some, it's trending toward a transition between when one era ends and the other begins.

DOUG FINKE

At Global Quantum Intelligence (GQI), we see a lot of roadmaps from quantum providers and fully expect continuing advances in the capabilities of both quantum hardware and quantum software during the next several years.

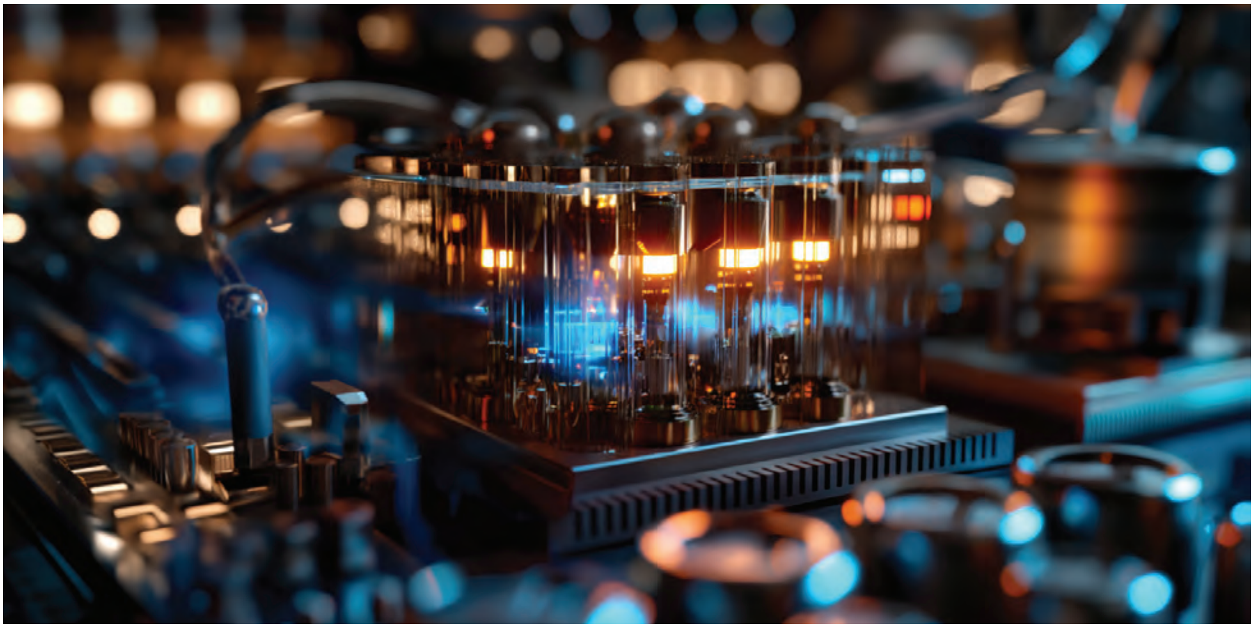
In fact, we believe we'll start seeing organizations using quantum technology for production purposes within the next few years. Some call it Quantum Advantage while others call it Quantum Utility, but in this article, I'll call it Quantum Production to distinguish it from one-off proof-of-concept experiments vs. those running the use cases on a repeated, regular basis.

Although we initially did not expect to see fault-tolerant quantum computers (FTQC) until the 2030s, recent advances lead us to believe that we'll start seeing what we call early FTQC processors available during the second half of this decade. One way we measure the capability of a quantum computer is a measure we call Quops, which stands for successful quantum operations. And we classify quantum evolution according to the following eras: Intermediate, Early, Large Scale, and Mature based upon how many Quops machines of that generation can process. Quops is a function of both the number of qubits available in a quantum processor and the logical error rate (LER) for these qubits.

For noisy intermediate-scale quantum (NISQ) processors, which don't have any error correction, the logical error rate will be the same as the physical error rate (PER). But in FTQC machines, which implement error correction codes that group together physical qubits to create a logical qubit, the LER will be much better than the PER. This is the purpose of error correction technology.

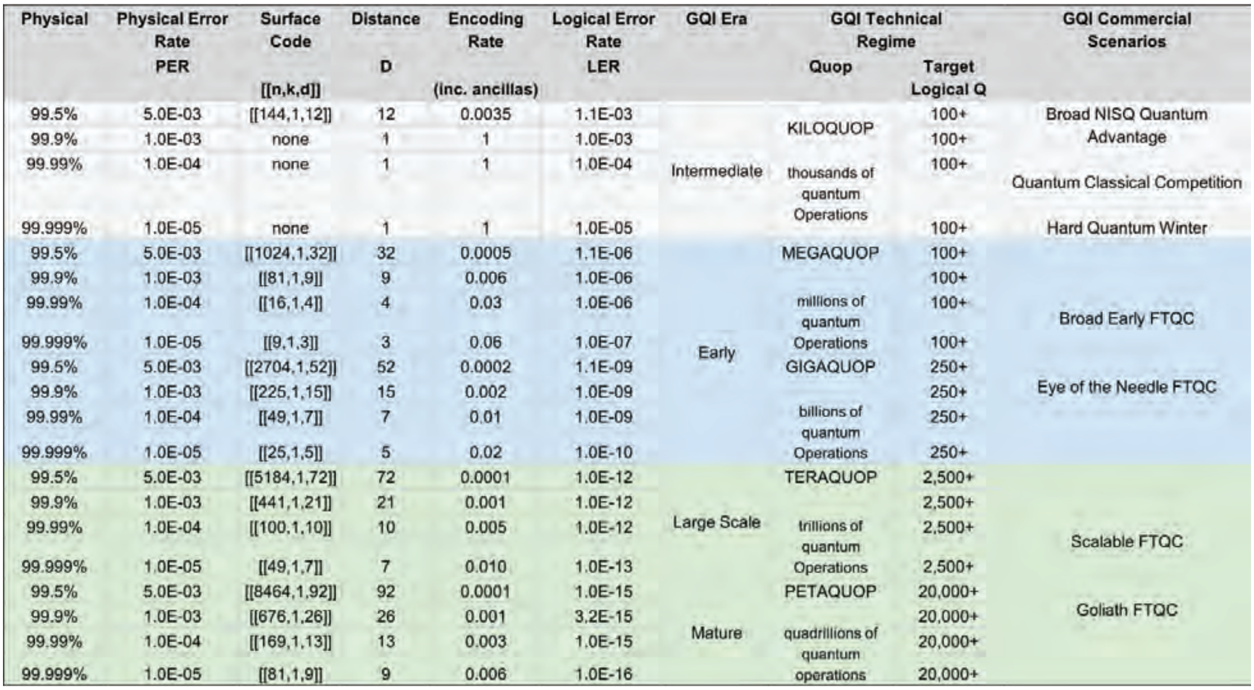
FTQC: Fault-tolerant quantum computers

We expect to see Early FTQC machines available within the next five years that can achieve capabilities within the MegaQuops or GigaQuops regimes. These initial machines may



ID 327272791 © Irochka | Dreamstime.com


LASER FOCUS WORLD



Physical	Physical Error Rate	Surface Code	Distance	Encoding Rate	Logical Error Rate	GQI Era	GQI Technical Regime		GQI Commercial Scenarios
	PER	[[n,k,d]]	D	(inc. ancillas)	LER		Quop	Target Logical Q	
99.5%	5.0E-03	[[144,1,12]]	12	0.0035	1.1E-03	Intermediate	KILOQUOP	100+	Broad NISQ Quantum Advantage
99.9%	1.0E-03	none	1	1	1.0E-03			100+	
99.99%	1.0E-04	none	1	1	1.0E-04		thousands of quantum Operations	100+	Quantum Classical Competition
99.999%	1.0E-05	none	1	1	1.0E-05			100+	Hard Quantum Winter
99.5%	5.0E-03	[[1024,1,32]]	32	0.0005	1.1E-06	Early	MEGAQUOP	100+	Broad Early FTQC
99.9%	1.0E-03	[[81,1,9]]	9	0.006	1.0E-06			100+	
99.99%	1.0E-04	[[16,1,4]]	4	0.03	1.0E-06		millions of quantum Operations	100+	
99.999%	1.0E-05	[[9,1,3]]	3	0.06	1.0E-07			100+	
99.5%	5.0E-03	[[2704,1,52]]	52	0.0002	1.1E-09		GIGAQUOP	250+	Eye of the Needle FTQC
99.9%	1.0E-03	[[225,1,15]]	15	0.002	1.0E-09			250+	
99.99%	1.0E-04	[[49,1,7]]	7	0.01	1.0E-09		billions of quantum Operations	250+	
99.999%	1.0E-05	[[25,1,5]]	5	0.02	1.0E-10			250+	
99.5%	5.0E-03	[[5184,1,72]]	72	0.0001	1.0E-12	Large Scale	TERAQUOP	2,500+	Scalable FTQC
99.9%	1.0E-03	[[441,1,21]]	21	0.001	1.0E-12			2,500+	
99.99%	1.0E-04	[[100,1,10]]	10	0.005	1.0E-12		trillions of quantum Operations	2,500+	
99.999%	1.0E-05	[[49,1,7]]	7	0.010	1.0E-13			2,500+	
99.5%	5.0E-03	[[8464,1,92]]	92	0.0001	1.0E-15	Mature	PETAQUOP	20,000+	Goliath FTQC
99.9%	1.0E-03	[[676,1,26]]	26	0.001	3.2E-15			20,000+	
99.99%	1.0E-04	[[169,1,13]]	13	0.003	1.0E-15		quadrillions of quantum operations	20,000+	
99.999%	1.0E-05	[[81,1,9]]	9	0.006	1.0E-16			20,000+	

Credit: Global Quantum Intelligence

contain a few thousand physical qubits that will translate to roughly a few 100 or so logical qubits. This should be enough to run a few useful applications, but still won't be powerful enough to run intensive quantum applications like Shor's algorithm that will require machines with TeraQuops capabilities. We don't expect those Large Scale FTQC machines to be available until the 2030s and they will provide thousands of logical qubits for calculations with potentially millions of physical qubits.

The chart demonstrates how error correction can improve the LER using one specific error correction code called the surface code as a function of the initial PER. As you might anticipate, the better the PER that the code starts with, the better the resulting LER will be. But another factor affects the physical qubits grouped together to create the logical qubit: we call it the physical-to-logical ratio. All else being equal, codes that have a larger physical-to-logical ratio will provide better error resistance. In the chart below, the third column describes the code being implemented with the notation <n,k,d>. The "n" indicates the number of physical qubits used within a group, the "k" represents the number of logical qubits that it creates, and the "d" stands for the distance between codewords within the encoding. The larger the distance, the more able that code is to detect and correct errors. Beyond the surface code used within this chart example, many other codes are being researched that may be more efficient, depending upon the code and the specific quantum processor it's being implemented on.

NISQ: Noisy intermediate-scale quantum

On the other hand, we also see advances occurring in more capable NISQ processors and associated algorithms that may also be able to run useful applications within the 2025 to 2029 timeframe. We've already seen a few companies demonstrate two-qubit fidelities of greater than 99.9% for their physical gates. And we've also seen advances in algorithms to get the most out of these physical gates. This software includes hybrid classical/quantum architectures, variational quantum algorithms, error mitigation and suppression techniques, circuit knitting, zero noise extrapolation, probabilistic error cancellation, and other classical post processing to improve quantum results. Moreover, the roadmaps we've seen indicate we may have available NISQ processors with 10,000 of physical qubits during the second half of this decade.

End users may have an interesting choice soon—within the next five years. Do they want to use an Early FTQC machine that provides about 100 logical qubits with two-qubit gate fidelities of greater than 99.9999%, or do they want to use a NISQ machine that contains around 10,000 physical qubits with two-qubit gate fidelities of 99.9% or perhaps 99.99%?

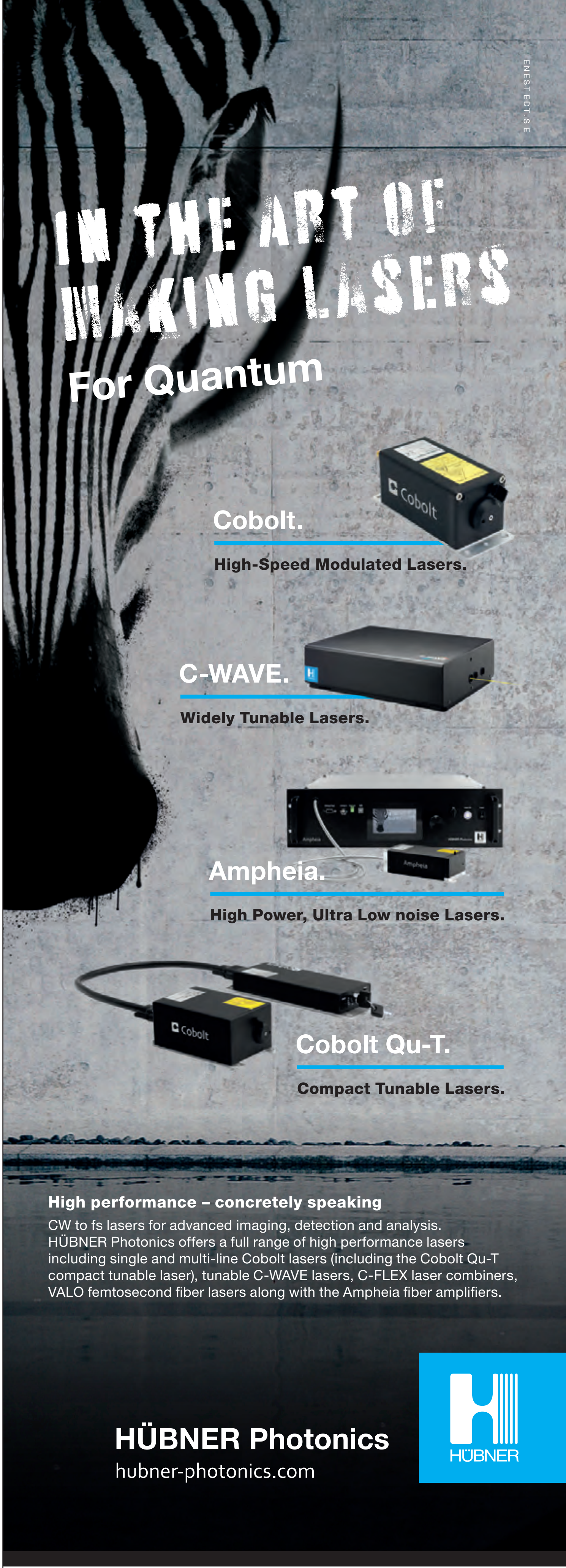
Many quantum researchers are skeptical anyone will ever run useful applications on a NISQ quantum computer. Beyond the fact that these machines still have noise issues, one of the other reasons is that many of these applications would rely on heuristic algorithms such as QAOA or VQE, which no one can theoretically prove will work. People will need to try them out to see if they work or not. On the other hand, theoretical proof exists that certain algorithms, such as Shor's algorithm, can run on a FTQC and provide an accurate answer. But we would remind our readers that many of the classical artificial intelligence (AI) algorithms that have become popular in recent days are also heuristic and computer scientists do not yet have a theoretical proof that they should work. Yet, of course, these AI algorithms do work.

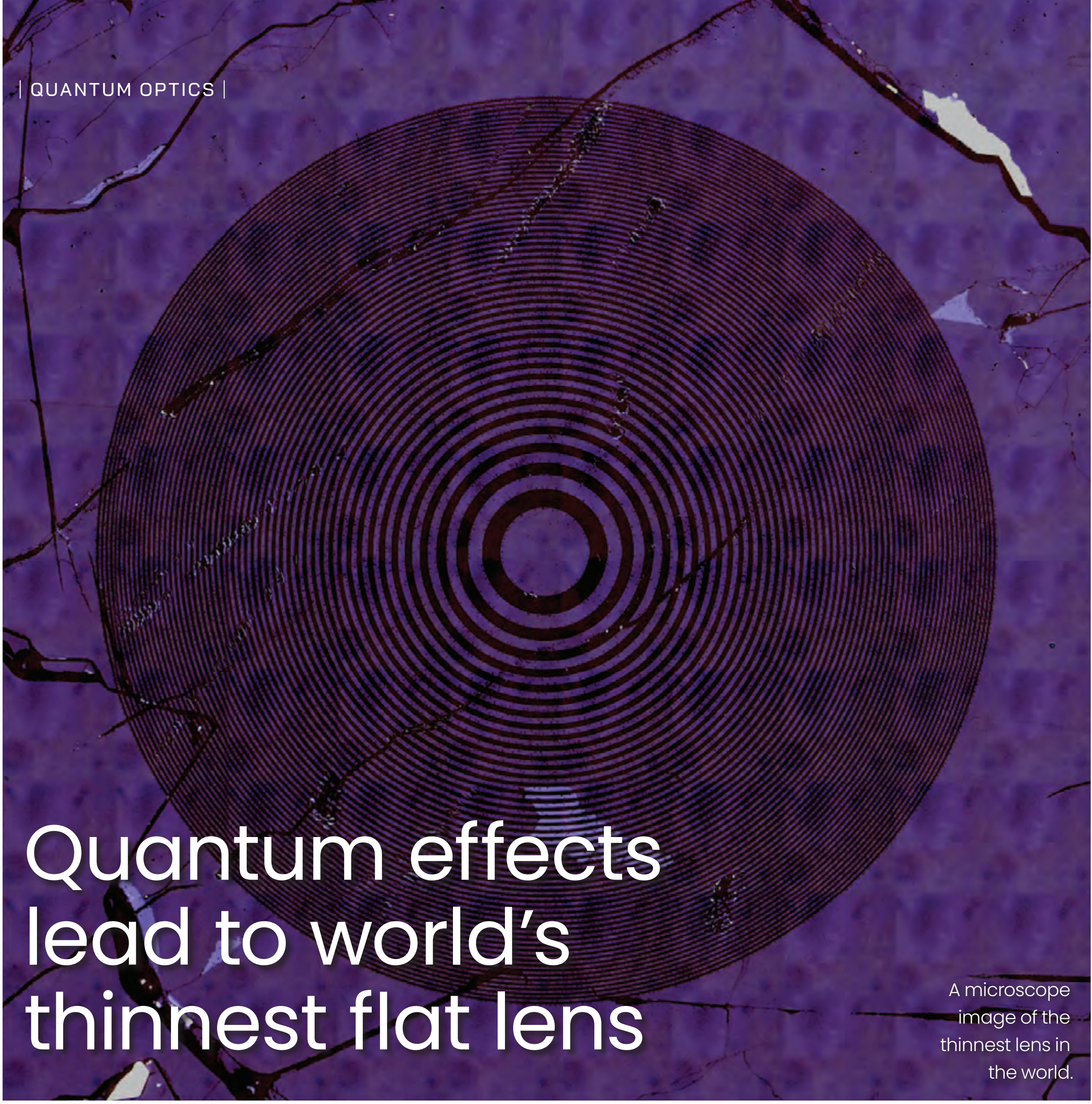
A particularly interesting paper we recently saw posted on *arXiv* is titled "A typology of quantum algorithms," authored by researchers at the Université Paris-Saclay and Quantinuum. In the paper, they classified 133 different quantum algorithms by a number of different factors, including whether the algorithm could be implemented on a NISQ processor or required a large-scale quantum (LSQ) processor. Of the 133 algorithms shown in the summary Classification Table at the end of the paper, a total of 50 were classified as potential candidates for using a NISQ processor, while the remaining candidates require a LSQ machine. It's possible one of these NISQ algorithms can indeed provide a usable commercial quantum production before the FTQC quantum computers are available.

We aren't at the point yet where we can definitely say which quantum applications will be able to provide commercially useful results on which machines. But the one thing that makes us optimistic is the diversity of innovative approaches and rapid advances organizations are making in both hardware and software to get us to the point where the systems can be used for quantum production for useful applications. Although some of these innovative approaches will fail, we fully believe that others will work and start delivering within the next few years on the promise of a quantum computer. The applications in production may only be a handful for the next few years, but this initial small number will grow substantially in the 2030s as more TeraQuop large-scale FTQC systems become available, which will enable many more algorithms to be run successfully.

While some may expect to see a hard demarcation between the end of the NISQ era and beginning of the FTQC era, in reality these eras will overlap and we'll see a gradual transition.

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





Quantum effects lead to world's thinnest flat lens

A microscope image of the thinnest lens in the world.

Image credit: L. Guarneri et al., Nano Lett., 24, 21, 6240–6246 [2024]; https://doi.org/10.1021/acs.nanolett.4c00694

Quantum mechanical exciton resonances of a two-dimensional (2D) quantum material inspire physicists to explore excitons as resonant building blocks for tunable next-gen anatomically thin optoelectronic metasurfaces.

SALLY COLE JOHNSON, EDITOR IN CHIEF

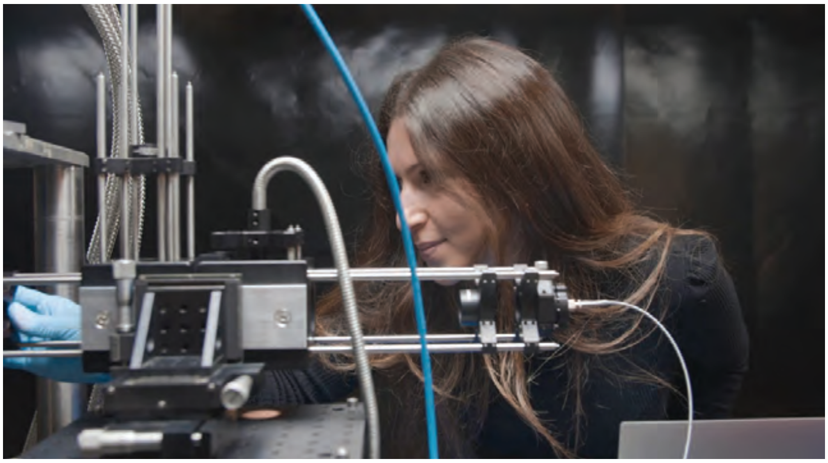
Thanks to quantum effects, a team of physicists led by Jorik van de Groep's 2D Nanophotonics group at the University of Amsterdam managed to create a flat lens a mere three atoms (0.6 nm) thick. Lenses are normally curved to refract and focus light, but the group's approach uses concentric rings of tungsten disulfide (WS_2) with gaps between them to form a Fresnel zone plate lens that focuses light via diffraction instead of refraction.

The magic comes from the size of the rings and distance between them—compared to the wavelength of light hitting it—and it determines the focal length of the lens. At the same time, the operation of the lens that focuses the light is dictated by the quantum mechanical exciton resonances of the monolayer, which allows WS_2 to absorb and re-emit light at specific wavelengths.

"While electronics are miniaturized, optics are still bulky," points out Ludovica Guarneri, a Ph.D. researcher working with van de Groep. "In fact, even the newest smartphones still have a camera sticking out of them. To solve this challenge, a new class of optical coatings—metasurfaces—were developed and a pattern of nanoscale structures collectively scatter light to perform an optical function, such as lensing in a ~100-nm-thick coating."

New 2D quantum materials, such as monolayers of transition metal dichalcogenides (TMDs) including WS_2, offer a remarkably strong and tunable light-matter interaction due to their quantum mechanical exciton resonances.

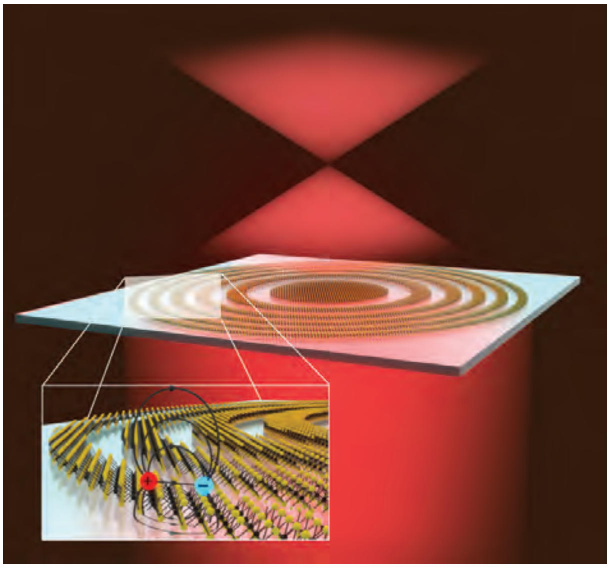
"We were intrigued by the properties of these materials and wondered whether we could leverage the excitons within this material as resonant building blocks instead of the nanostructures in established metasurfaces," Guarneri says. "This resulted in our work, in which we set out to develop a new generation of optoelectronic metasurfaces—pushing the size down to atomic thicknesses."



Ludovica Guarneri working on the setup for their lens. *(Photo credit: University of Amsterdam's Institute of Physics)*

Lens design work

Fabrication of the team's lens requires several cleanroom steps. It starts out with a high-quality, large-area monolayer of WS_2 on a sapphire substrate, which is achieved via gold-assisted exfoliation. During this process, the outer atomic layer is peeled off a source crystal using a flexible tape made of gold and then transferred onto the sapphire substrate.



The world's thinnest lens is made of concentric rings of tungsten disulfide, and it uses excitons to efficiently focus light. Bottom left: An exciton/excited electron bound to the positively charged hole within the atomic lattice.

(Image credit: Ludovica Guarneri and Thomas Bauer)

"Our atomically thin lens is created by directly patterning the monolayer via electron-beam lithography and reactive-ion etching," says Guarneri. "The design is a Fresnel lens, a.k.a. zone-plate lens, optimized to focus light at a 620-nm wavelength, which is the spectral location of the strongest WS_2 exciton resonance, 1 mm away from the surface."

When the team characterized the focusing efficiency spectrum of the lens around resonance, they discovered its spectral line shape mirrors the electronic susceptibility of the material.

"The electronic susceptibility of monolayer WS_2 is, in turn, governed by exciton resonance," explains Guarneri. "To further explore the relationship between excitons and the functionality of the lens, we studied both the focusing efficiency and optical properties of the material as a function of temperature."

It turns out, lowering the temperature directly affects the nonradiative decay rate of the exciton and it leads to an increased excitonic quantum yield. Acting on the excitons' recombination rates "impacts the focusing efficiency of the lens, which increases as the temperature is lowered—and it proves the spectral-line shape of the focusing efficiency is dictated by the excitonic decay rates," Guarneri says.

Biggest hurdle involved in this work? Measuring the temperature-dependent data. In fact, it required building a custom optical setup around a helium cryostat, which meant the team needed to measure the focus formed inside the cryostat by positioning an optical imaging and laser setup outside the cryostat.

"It required very careful design and alignment," says Guarneri. Acquiring the measurements was also a delicate procedure, because they probed a tiny signal—light focused by the lens—on top of a large background (light being transmitted through the nearly transparent substrate).

"Lastly, the data analysis was quite involved and required a lot of thinking outside the box, since we wanted to carefully quantify the fraction of the incident power that was focused by the lens," Guarneri says.

The coolest part of this work for Guarneri was the first time she saw on the camera that light was actually being focused by such a thin lens—~0.6 nm. "Next to this, it was truly fascinating to read the strong fingerprint of the excitons on the performance of the lens—its focusing efficiency spectrum," she adds.

Anatomically thin optical metasurfaces based on exciton resonances

With this work, the physicists are paving the way to a class of anatomically thin optical metasurfaces based on exciton resonances, where light is manipulated within a single layer of atoms. The low efficiency that characterizes these elements can be used as an advantage for applications where transparency is a benefit—eyewear such as eye tracking, virtual reality (VR), and augmented reality (AR) goggles.

"In our next work, we'll leverage the tunability of the exciton resonances within monolayer TMDs to obtain dynamic metasurfaces where the designed operation can be actively modified," says Guarneri. "These 2D quantum materials have a refractive index that can be tuned electrically, which is a direct result of the exciton resonance."

This tunability is unique to optical materials, which typically have a fixed refractive index. "Using this, we want to create atomically thin optical coatings that can change their optical function on demand—steer light to the left or right using electrical voltages, for example, or change the focal distance of a lens. It could have a major impact on technologies where active control over light is essential, such as AR/VR, optical communications, and LiDAR," Guarneri says.

FURTHER READING

L. Guarneri et al., *Nano Lett.*, 24, 21, 6240–6246 (2024); https://doi.org/10.1021/acs.nanolett.4c00694.

Overcoming inefficiency for quantum light generation

Fundamental studies provide new insights into efficiency of single-photon production from quantum defects.

MARK E. TURIANSKY AND **CHRIS G. VAN DE WALLE**

Quantum technologies promise to revolutionize the fields of computing, communications, and sensing. Inherent in realizing this promise is the ability to *transmit* quantum information.

Photons are natural candidates for the task: Unlike other quantum particles, such as electrons, photons interact very weakly with their environment, allowing them to coherently store information while propagating.

Photons are widely used as the basis for the transmission of classical information. Decades of intense research efforts and optimization have produced fiber-optic cables that can transmit photons with extremely low loss—the impact of these discoveries was recognized with the Nobel Prize in Physics in 2009. This low-loss transmission makes fiber-optic cables superior in both transmission distance and bandwidth compared to electrical cables. Fiber-optic connections currently carry the internet; we should anticipate that they will also sustain the "quantum internet" of the future.

An important restriction is that low-loss transmission only works for light in a narrow range of wavelengths, known as the telecom wavelength band. In addition, a key difference with classical technologies is that quantum information needs to be encoded a single photon at a time, requiring specialized techniques for the generation of such photons.

Single photons in a well-defined quantum state can be produced using

FIGURE 1. Schematic rendition of a quantum defect emitting a single photon. *(Image credit: Mark E. Turiansky)*

a variety of sources, but atomic-scale imperfections—"quantum defects"—in crystals have emerged as excellent candidates (see Fig. 1). In contrast to defects in classical devices, which are often detrimental, in the case of quantum defects "the defect is the device" (a phrase coined by the late Audrius Alkauskas, echoing Herbert Kroemer's famous statement about interfaces). The prototype quantum defect, the nitrogen-vacancy (NV) center in diamond, has already been widely used to demonstrate the fundamental components of a quantum network. But the photons produced by the NV center are in the visible spectrum, far from the desired telecom band. Extensive research efforts have been devoted to finding quantum defects that produce telecom-wavelength photons, but producing single photons with high efficiency has proven challenging.

Our team at the University of California, Santa Barbara, has now uncovered the origin of these difficulties—pointing the way to approaches to surmount them.

Quantum defects as single-photon emitters

The fact that quantum defects are embedded in a crystalline lattice offers many advantages—first and foremost, the ability to manipulate atom-like properties without having to worry about confining atoms in free space. Using the crystalline lattice as a framework for holding the quantum emitter unfortunately also has a downside: Atoms are always in motion, and these vibrations can drain energy away from a quantum defect. This phenomenon is known as electron-phonon coupling, where the electronic states of the defect interact with the vibrations (phonons) of the crystalline lattice.

After optical excitation, we expect our quantum defect to emit a photon, but due to electron-phonon coupling, the energy may instead be drained away in the form of phonons. When electron-phonon coupling is strong, this process will severely reduce the efficiency of single-photon emission. Empirically, it had been observed that this efficiency loss becomes more severe at longer wavelengths (toward the telecom band). We focused on developing theoretical methods and simulations that model these processes from first principles, thus developing predictive tools that can explain why the losses so strongly depend on wavelength.

Indeed, our modeling shows that the efficiency decreases *exponentially* as the emission wavelength increases from the wavelengths of visible light (violet to red) to the infrared wavelengths in the telecom band (see Fig. 2). Importantly, our simulations allow us to identify promising avenues for engineering brighter emitters. Careful choice of the material that hosts the quantum defect is important. In addition, atomic-level engineering of the vibrational properties (both of host and defect) will prove fruitful. We proposed materials such as gallium nitride or aluminum nitride, which are already a technologically mature platform, as promising hosts.

Tackling the efficiency challenge

Another approach involves coupling to a photonic cavity, a topic that benefited from the expertise of Dr. Kamyar Parto and Prof. Galan Moody, collaborators in the UC Santa Barbara Quantum Foundry. When coupled to a photonic cavity, the rate at which a defect emits

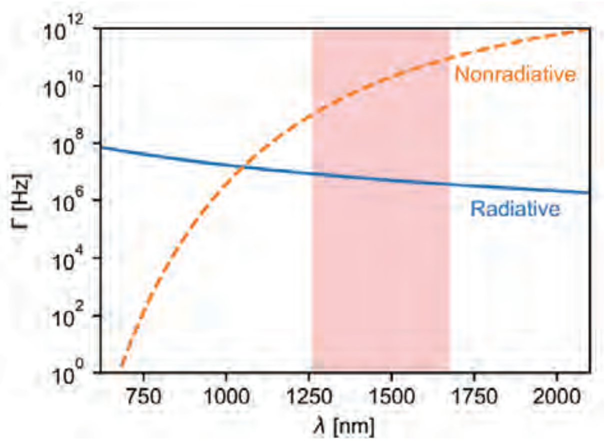


FIGURE 2. Radiative (solid blue line) and nonradiative rate Γ (dashed orange line) for a typical quantum defect as a function of wavelength. The range of telecom wavelengths is shaded in pink. *(Image credit: Mark E. Turiansky)*

photons is increased (the so-called Purcell enhancement), while processes enabled by electron-phonon coupling remain constant, and this enhances efficiency.

We should also not solely focus on quantum defects that directly emit at telecom wavelengths. Quantum frequency conversion can be performed with remarkably high efficiency. The ideal emitter might operate at shorter wavelengths, with photons converted to telecom wavelengths prior to transmission.

In our opinion, the "Goldilocks" emitter is still out there. Given the success of the NV center, a great deal of work has focused on diamond as a host material; exploration of alternative host materials is lagging but could prove hugely fruitful.

Overall, the insights provided by our modeling should prove useful for rational design of novel quantum emitters that will ultimately enable long-distance transmission of quantum-encoded information.

FURTHER READING

M. E. Turiansky, K. Parto, G. Moody, and C. G. Van de Walle, *APL Photonics,* 9, 066117 (Jun. 26, 2024); https://doi.org/10.1063/5.0203366.

Mark E. Turiansky is a postdoctoral researcher and Quantum Foundry Fellow and **Chris G. Van de Walle** is a distinguished professor and the Herbert Kroemer Chair in Materials Science, both at the University of California, Santa Barbara; e-mail: mturiansky@ucsb.edu; https://quantumfoundry.ucsb.edu and https://vandewalle.materials.ucsb.edu.

Conventional internet meets quantum internet?

A transmitter-receiver concept to transmit entangled photons over optical fiber may enable transmitting both the quantum and conventional internet on the same fiber.

SALLY COLE JOHNSON, EDITOR IN CHIEF

A team of four physicists at the Institute of Photonics at Leibniz University Hannover in Germany recently came up with a potential solution to combine the conventional internet with the quantum internet—enabling two different types of light to coexist on the same frequency channel.

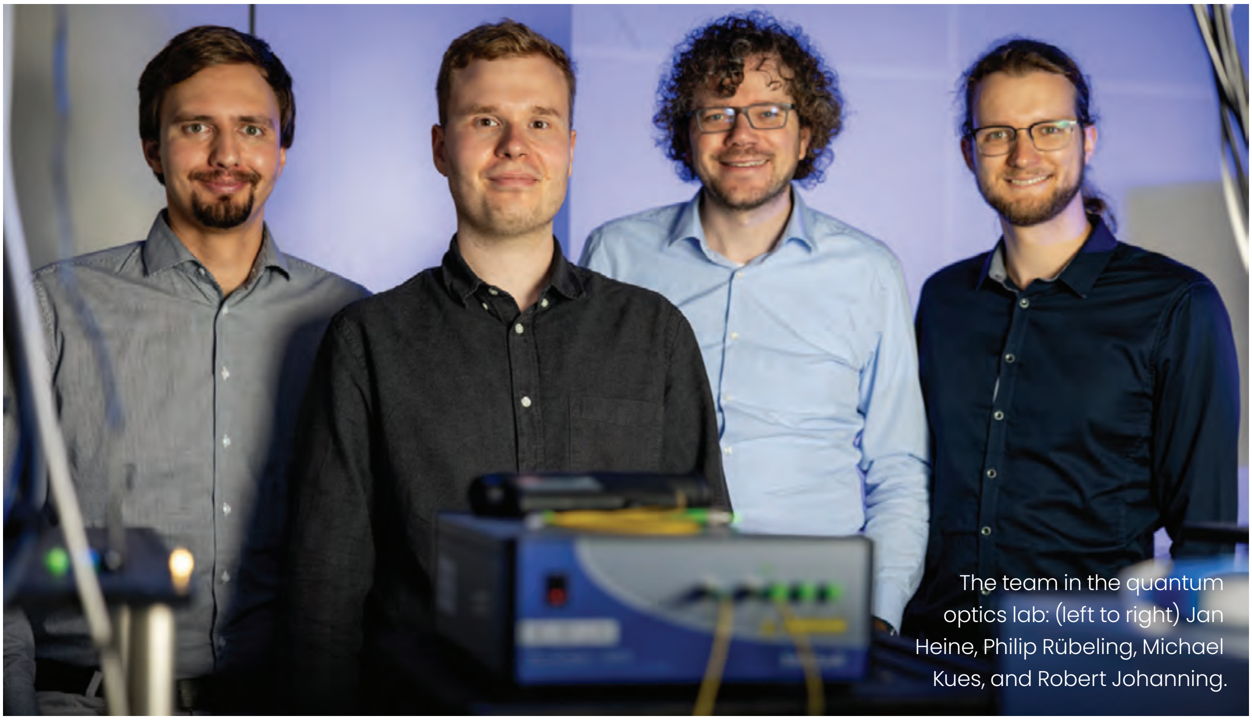
In an experiment, they proved photonic entanglement is maintained even when the photons are sent together with a laser pulse. It allows them to change the color of the laser pulse with a high-speed electrical signal to match the color of the entangled photons. This means they can combine and separate laser pulses and entangled photons of the same color within an optical fiber.

"Our work was driven by the need to integrate quantum communications into existing fiber-optic networks," says Michael Kues, head of the Institute of Photonics at Leibniz University Hannover. "The challenge of combining quantum and classical data transmission on the same fiber sparked our interest—particularly in advancing the development of a secure quantum internet."

Serrodyne shifting technique

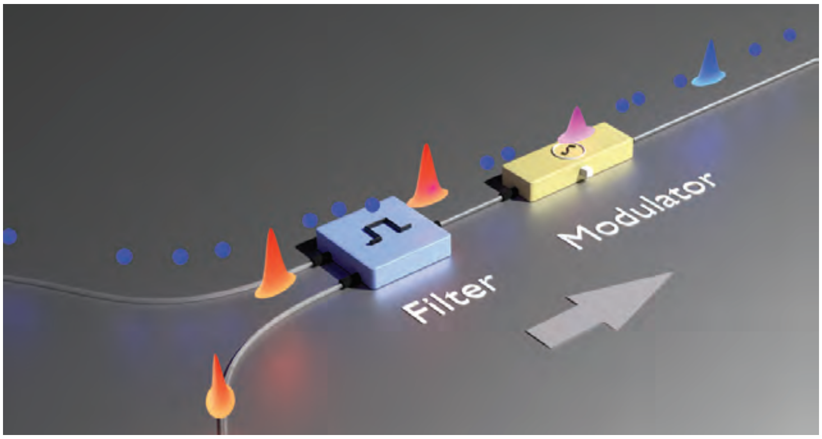
The core concept behind the team's work is the serrodyne shifting technique, which involves using a linear temporal phase ramp to translate the spectrum of an optical pulse. This allows the color of the laser pulse to be changed by modifying its temporal phase.

"It basically adds energy to the light, or removes energy, which changes its color," explains Kues.



The team in the quantum optics lab: (left to right) Jan Heine, Philip Rübeling, Michael Kues, and Robert Johanning.

Photo credit: IOP



Schematic of the team's serrodyne hybrid transceiver. *(Image credit: IOP)*

"It's important that laser pulses and electronic pulses (used for the phase manipulation) arrive simultaneously. For the rest of the time, the electronic signal is off, so entangled photons are transmitted unperturbed. It allows these different types of light to coexist on the same frequency channel—which enables efficient use of bandwidth."

For their design work, the team combined a complex interplay of quantum photonics and microwave technology, which provided them with completely new insights and challenges that needed to be understood.

"As an example, we require precise control of the interaction between the electronic signal and the laser pulses, which we achieve by controlling their arrival time," Kues says. "Great care went into minimizing drifts in the arrival time difference between the two signals. To do this, we used a stabilized mode-locked laser and a sophisticated multichannel electronic signal generator for the multi-gigahertz regime."

A large challenge for the team was to minimize the optical loss within the transceiver, because too much loss would make the reconstruction of the quantum state challenging. "In the future, we see great potential in integrating the fiber-coupled transceiver components into a single photonic integrated circuit to minimize the loss and enable greater performance of the frequency shift," Kues says.

Exciting moments

Two of the most exciting moments for the team involved shifting the frequency of the laser pulses, and the cancellation after turning on the inverse signal on the second phase modulator.

"The cancellation of the frequency shift is remarkably good," says Philip Rübeling, who is pursuing a Ph.D. at the Institute of Photonics. "And the second moment was seeing the effect on the quantum signal. Demonstrating that entangled photons can be transmitted by the serrodyne transceiver on the same frequency channel as classical laser light and separated again without losing their quantum properties is a great result for this work."

> This work paves the way for the next generation of telecommunications.

Before now, it wasn't possible to use both transmission methods per color within an optical fiber because the "entangled photons block a data channel in the optical fiber, which prevents its use for conventional data transmission," says Jan Heine, a doctoral student working with Kues.

The experiment showed that photons can be sent within the same color channel as the laser light, which suggests that all color channels can still be used for conventional data transmission—and a mixed or hybrid quantum and conventional network can succeed.

What's ahead

This work paves the way for the next generation of telecommunications, including quantum key distribution over existing fiber networks. "It could lead to the development of a secure quantum internet and enhance data security for critical infrastructure," says Kues. "We also contributed to the understanding of electro-optic manipulation of quantum light by discovering and investigating the different serrodyne dynamics for frequency-entangled photons."

The next steps will involve "demonstrating the serrodyne transceiver concept within a deployed fiber link, which works in a truly hybrid way, to transmit entangled photons and classical data at the same time," says Kues.

FURTHER READING

P. Rübeling, J. Heine, R. Johanning, and M. Kues, *Sci. Adv.*, 10, eadn8907 (2024); https://doi.org/10.1126/sciadv.adn8907.

Microstructured optical fibers for quantum computing?

University of Bath physicists create microstructured hollow-core optical fibers to handle data transfer challenges expected with quantum computing.

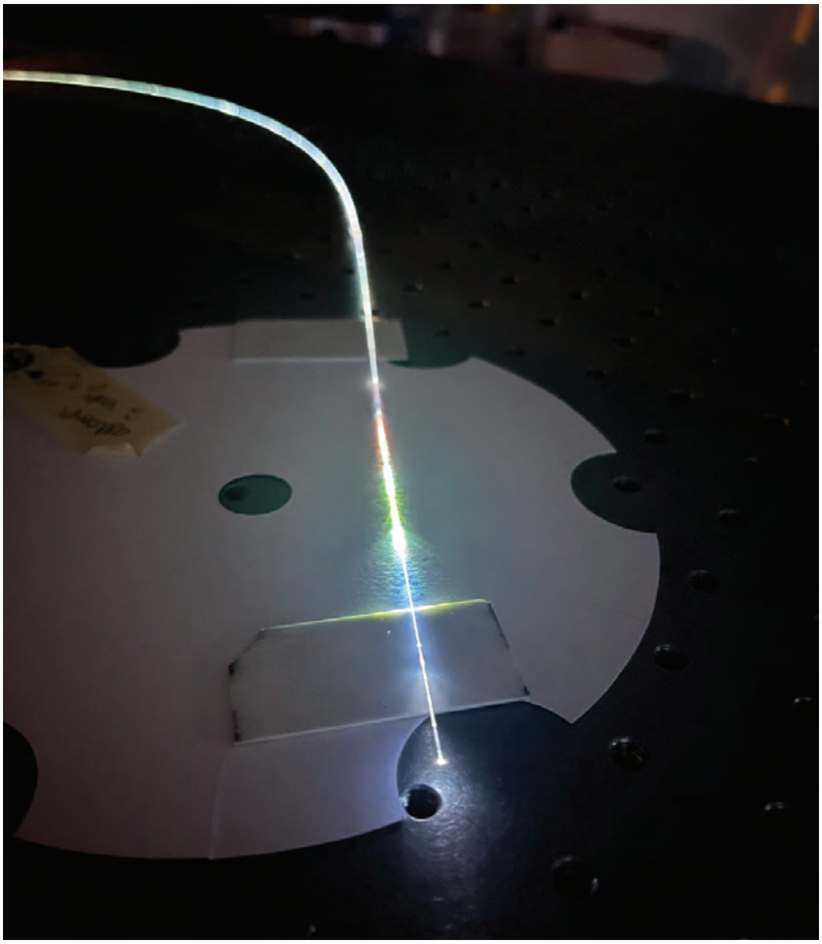
SALLY COLE JOHNSON, EDITOR IN CHIEF

To unleash the full power of quantum computing, an international team of researchers led by physicists at the University of Bath's Centre for Photonics and Photonic Materials in the U.K. are designing specialty fibers with a microstructured core, which consists of a complex pattern of air pockets running along the entire length of the fiber. Its air pocket patterns enable the researchers to manipulate the properties of light within the fiber to create entangled pairs of photons, change their color, or trap individual atoms inside the fibers.

Why the need for specialty fibers? Unfortunately, optical fiber networks designed for telecommunications today transmit light at wavelengths not compatible with the operational wavelengths of quantum computing's light-based silicon-photon sources, qubits, and active optical components. And the solid cores of these optical fibers are likely suboptimal for quantum technologies as well.

"Optical fibers offer the prospect of creating fully integrated quantum devices, without the need for interfacing and aligning with free-space components," says Dr. Kristina Rusimova, a lecturer in the Department of Physics at Bath. "This is promising for reducing the losses of such devices, which could be a major breakthrough for the field—retaining the single photon for long enough to be interacted with another single photon is an underpinning challenge for the technology."

Beyond this, fibers and fiber-based devices can readily be integrated into existing optical fiber networks. Microstructured optical fibers are extremely versatile and offer a flexible solution across a broad



Microstructure fiber post-process and illuminated with white light. *(Image credit: Kerrianne Harrington)* range of applications. They are used as both sources, communication channels, sensors, and active optical components.

A hollow-core fiber design

Hollow-core fibers are more challenging to manufacture than solid-core fibers due to their thin-wall glass microstructures that serve as their cladding. "These thin structures can be difficult to control during the drawing process in a furnace, where large glass structures are transformed into optical fibers," says Dr. Kerrianne Harrington, a postdoctoral physics researcher at Bath.

But recent advances in fabrication techniques and structural design enabled hollow-core fibers to achieve lower loss than traditional telecommunication fibers.

"Ongoing improvements are expanding the performance of such fibers across a broad range of wavelengths, which makes them suitable for optical quantum systems," Harrington adds. "Hollow-core fibers can be used as long-distance communication channels to reduce the need for quantum repeaters; they also offer low latency, low optical nonlinearity, and can be used for vessels for atom-based quantum devices—enabling longer interaction lengths and increased optical depth, tighter confinement, and easy integration with other fibers."

Photonic crystal fibers also offer tunable nonlinearity, which Harrington points out is useful in quantum resource state generation over a range of operational wavelengths.

The fiber fabrication facility at Bath is "the only one within the U.K. fully dedicated to the development and fabrication of microstructured optical fibers of this kind," says Rusimova.

Snapshot of the optical fiber fabrication process—glass is pulled into a cane structure. *(Image credit: Kerrianne Harrington)*

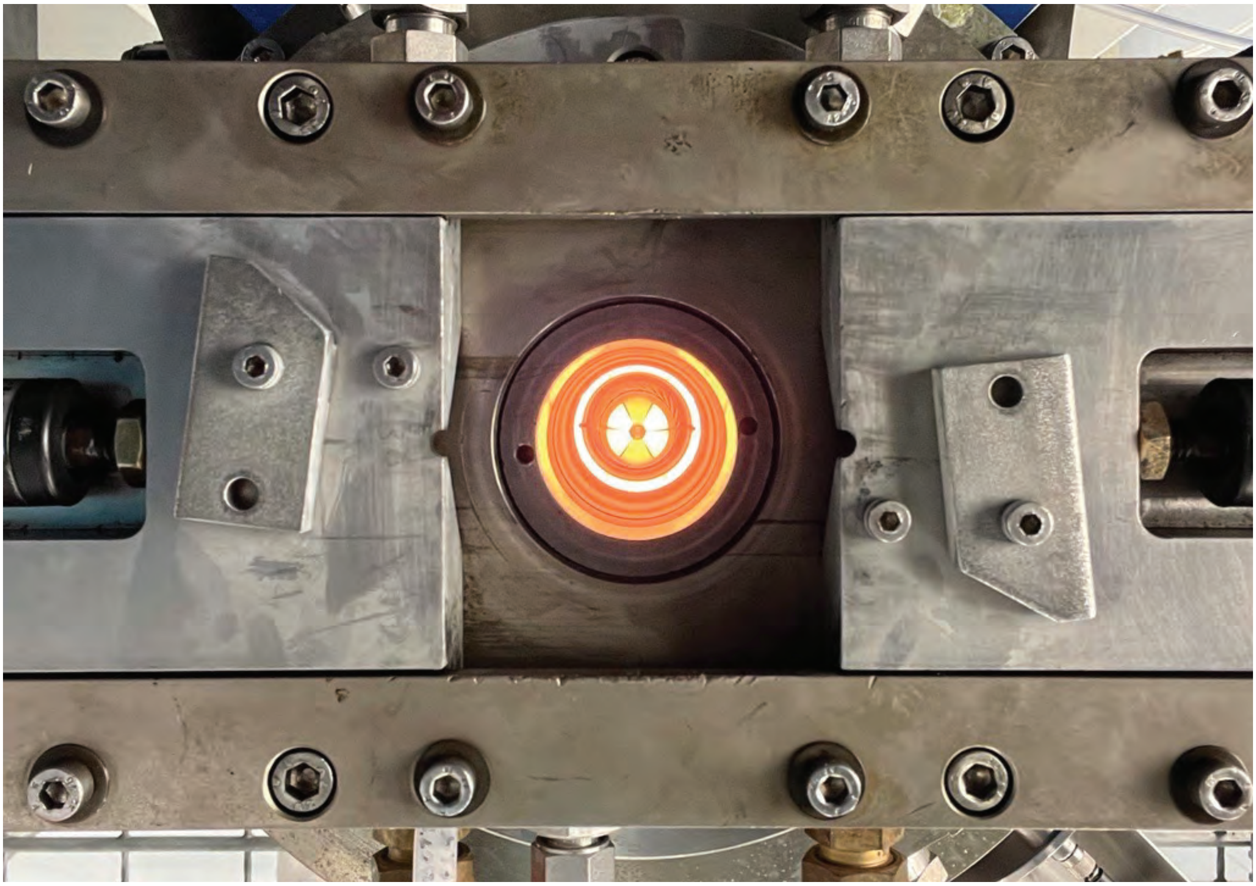
"Key benefits to society include the prospect of ultrasecure communications and quantum computers that offer unparalleled computational power and can simulate the complex molecules involved in the fabrication of new drugs and materials."

Major challenges ahead for the field include achieving low-loss integration between fiber-based components and on-chip quantum devices, as well as reliably trapping atomic vapors inside optical fibers without the need for a vacuum system attached to them.

Sources of noise, like Raman scattering, are also a big challenge for most quantum applications. And it will be necessary to achieve a consistent yield and overcome microbends and mechanical stress within hollow-core fibers, which currently prevent their use for long-distance communications.

Frequency conversion and generation of multiplexed single photons

The most interesting applications for their hollow-core fibers, the team



Inside the optical fiber furnace, the glass is heated and formed into a neck down. *(Image credit: Kerrianne Harrington)*

says, are frequency conversion and to generate multiplexed single photons. The former allows them to interface components of quantum networks that operate at different wavelengths to one another, such as sources, memories, or transmission lines.

Significantly, the work at Bath marks the first demonstration of a fiber that can perform quantum frequency conversion over a broad range of wavelengths. And multiplexed state generation overcomes the inherently probabilistic nature of quantum sources to enable a source with high enough efficiency for quantum applications.

Microstructured optical fibers ahead

Optical fibers can be integral to any component of a quantum device and have many applications ranging from secure communications, quantum computing, accurate timing, and distributed sensing. "Recent progress in these areas has been quite rapid, with demonstrations of quantum entanglement distribution on city-scale distances, and we think these technologies will be part of our lives in the not-too-distant future," says Dr. Alex Davis, an ESPRC Quantum Career Acceleration Fellow at Bath.

> Optical fibers can be integral to any component of a quantum device.

"We anticipate that in the near-term these systems will play a key role in future quantum networks and other quantum technologies," says Davis. "Especially exciting is the prospect of using these fibers to generate exotic new quantum states to use as a resource for quantum computing, to connect photonic architectures that span a range of wavelengths, and to combine the unique waveguiding properties of fiber with quantum interactions enabled by atomic ensembles. To get there, we need to overcome key challenges around integration, loss, noise, and yield."

FURTHER READING

C. McGarry, K. Harrington, A. O. C. Davis, P. J. Mosley, and K. R. Rusimova, *APL Quantum*, 1, 030901 (2024); https://doi.org/10.1063/5.0211055.

Terahertz metasurface optical cavity 'light trap' creates quantum states

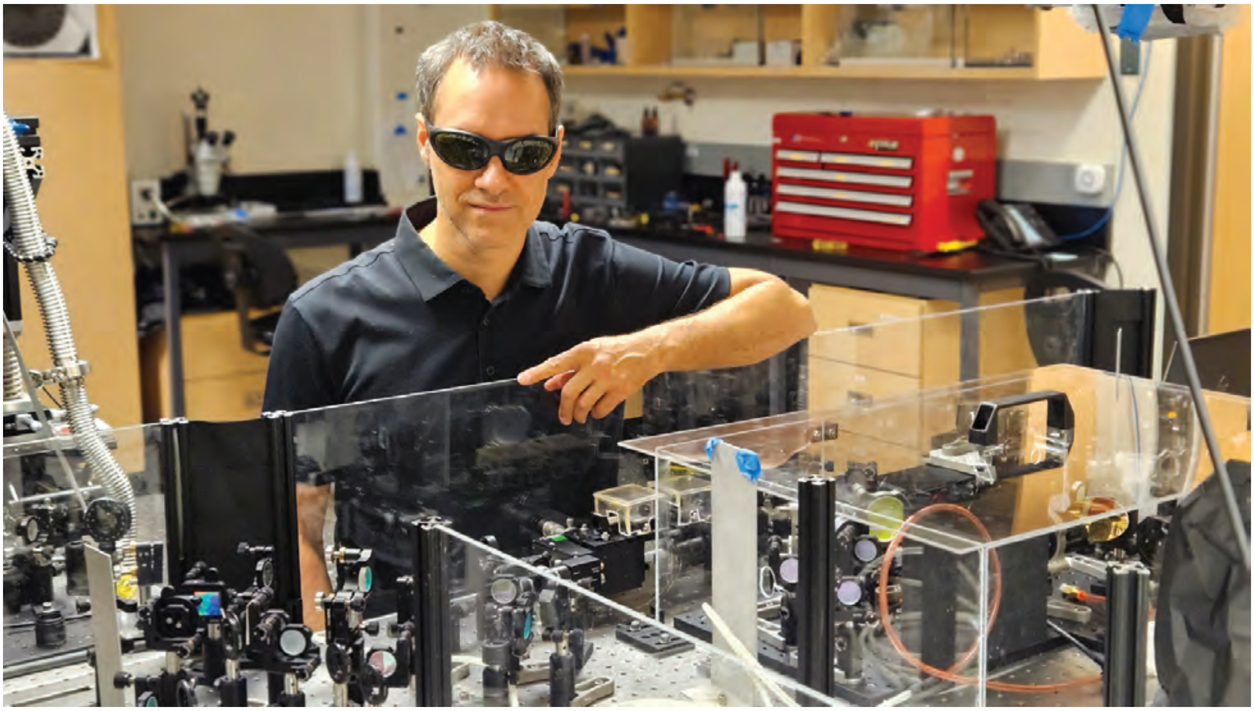
Scientists sugar-coat terahertz (THz) metasurfaces to hybridize molecules with THz light—and demonstrate a new optical cavity design—to explore the unique properties of strongly coupled quantum states.

SALLY COLE JOHNSON, EDITOR IN CHIEF

A group of scientists led by Professor Jean-Michel Ménard at the University of Ottawa in Canada has shown that THz metasurfaces—which can be fabricated at large scale and relatively low cost—are a robust and efficient platform to hybridize molecules with THz light. And their platform offers an alternative to the standard cavity design to explore and harness the unique properties of strongly coupled quantum states.

Perhaps even more importantly, strongly coupled quantum states that involve molecules offer the possibility to control fundamental building blocks of life.

To create a metasurface optical cavity "light trap" within a two-dimensional (2D) plane, Ménard's Ultrafast Terahertz Spectroscopy group teamed up with Claudiu Genes' Cooperative Quantum Phenomenon research group at the Max Planck Institute for the Science of Light in Germany, and Iridian Spectral Technologies, an Ottawa-based company that specializes in optical filters. When sugar-coated (with glucose), the group's metasurface triggers a strong



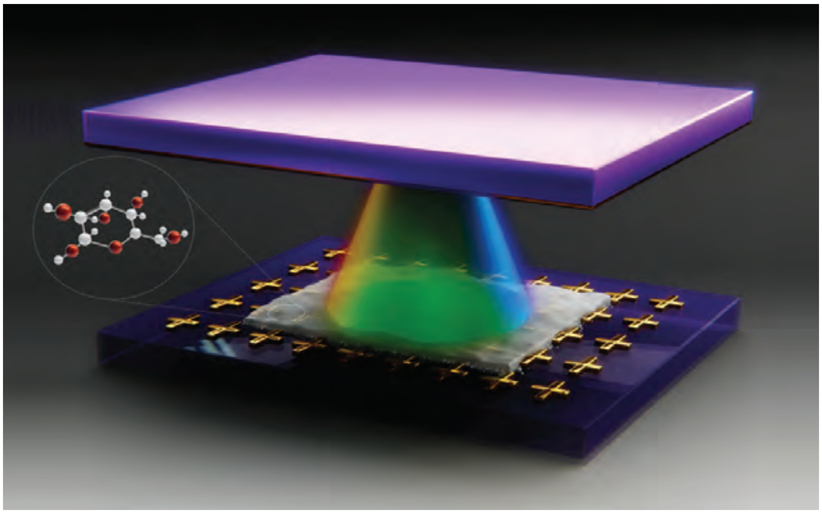
Professor Jean-Michel Ménard in the lab with his group's setup. *(Photo credit: Breeana Elliot)* interaction between THz light and glucose molecules.

Strong coupling between light and molecules

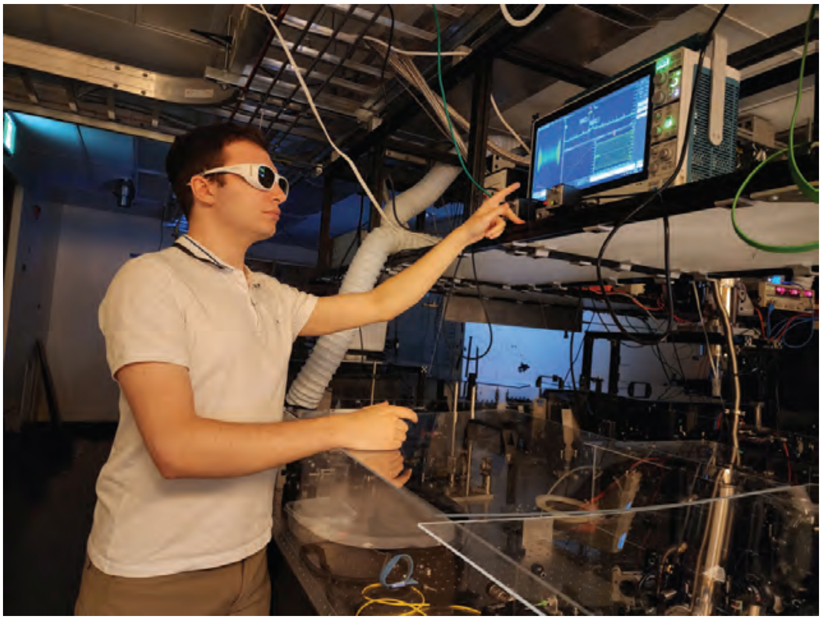
The group's work centers on the concept that strong coupling between light and an ensemble of molecules requires three conditions: "A tight spatial confinement of the light, a high number of molecules, and a high likelihood that molecules can absorb and reemit a photon trapped inside the cavity," explains Ménard.

Glucose has a strong and narrow absorption line centered at a frequency of 1.43 THz, which satisfies the last condition. Knowing this allows the group to design a complementary high-quality optical resonator (cavity/metasurface) to trap this THz radiation while compacting as many glucose molecules as possible on this surface.

To ensure high-density glucose deposition, they developed a spray coating technique akin to how cars are painted. "The main difference? We use a solution of glucose instead of paint color," Ménard says. "Under precise experimental conditions, the molecules couple to the electromagnetic mode trapped within the metasurface to create hybrid states. And these states called 'polaritons' aren't uniquely matter nor light—their quantum superposition gives them unique properties."



Schematic of the group's full sample architecture with metasurface, glucose, and mirror. *(Image credit: Genes Design)*



Ahmed Jaber, a Ph.D. student in Ménard's group, at work in the lab. *(Photo credit: Eeswar Yalavarthi)*

A new optical cavity 'light trap' design

Since pioneering work began within this realm during the 1990s, research into strong light-matter interactions has largely relied on one type of optical device with an optical cavity that consists of two mirrors facing each other, with a semiconductor material sandwiched in between.

By replacing the semiconductor material with organic molecules, the regime of strong light-matter coupling can fundamentally modify the properties of molecules—and it can lead to surprising effects such as a change in chemical reaction rates. This potential to gain control of chemical reactions has far-reaching applications for many fields, particularly health and medicine.

It motivated the group's quest to create a new type of cavity to efficiently trap THz light, which is located within the deep infrared region of the electromagnetic spectrum and can strongly interact with molecules.

While experimenting with cavities and metasurfaces, a revelation hit the group: the two can be combined. Crafting a cavity out of a metasurface and positioning a flat metallic mirror—so they face each other—above it substantially enhances the strength of the light-matter interaction by about 2x compared to a standalone planar cavity.

"This discovery encouraged us to explore the physics of why we saw such an improved enhancement and we discovered these hybrid cavity/metasurface architectures can enhance the electric field strength of light within them in a way that combines the benefits of both cavities and metasurfaces," says Ahmed Jaber, a Ph.D. student in Ménard's group. "Our results show that hybrid architectures facilitate stronger hybrid states."

What goes into their optical cavity's simple design? First, a metasurface is crafted from a planar array of metallic crosses, which each have a length of 60 μm and are periodically separated by 100 μm. A thin film of glucose (an organic material) then gets sprayed onto this surface.

> No precise alignment is needed to trap the light.

A mirror can be positioned facing this metasurface to ensure light gets trapped to form a highly localized photonic mode, which increases the THz interaction with glucose.

It's important to note: no precise alignment is needed to trap the light, thanks to the geometry of the metasurface's metallic pattern. And the group's platform is essentially plug-and-play, which means other organic materials can be used in it to create a range of different quantum systems with new properties.

"One of the biggest challenges that must be overcome is to gain a better understanding of the fundamental light coupling mechanism to an ensemble of molecules," Ménard points out. "Is the light affecting one molecule at a time or all of them simultaneously?"

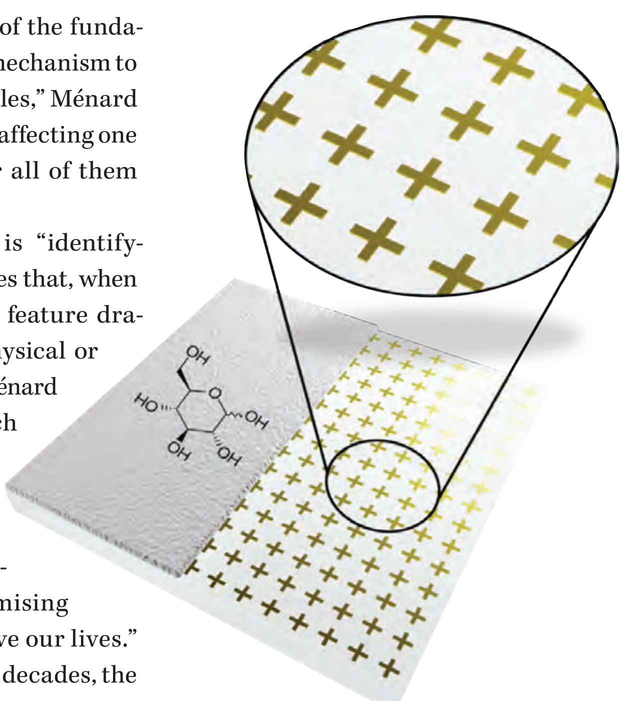
Another challenge is "identifying families of molecules that, when hybridized with light, feature dramatically modified physical or chemical properties," Ménard says. "Hopefully, such molecules can play a key role in environmental, health, or energy transport applications to enable promising applications to improve our lives."

Prior to the past two decades, the THz region was largely unexplored by the scientific community because techniques for its generation and detection were inefficient, and optical components—lenses, polarizers, etc.—were difficult or cost-prohibitive to fabricate.

"A lot of our group's effort went into developing efficient techniques for THz spectroscopy," says Ménard. "With our collaborators, we also developed 2D planar surfaces, or metasurfaces, to select specific spectral components, modify the spatial distribution, and increase the local intensity of THz light."

Modified chemical reaction applications ahead?

One of the most intriguing applications of strong light-matter coupling with molecules is exploring modified chemical reactions. "When light-matter coupling is fundamentally altering the vibrational bonds of a molecule, it should have a defined effect on chemical reactions that involve these bonds," says Ménard.



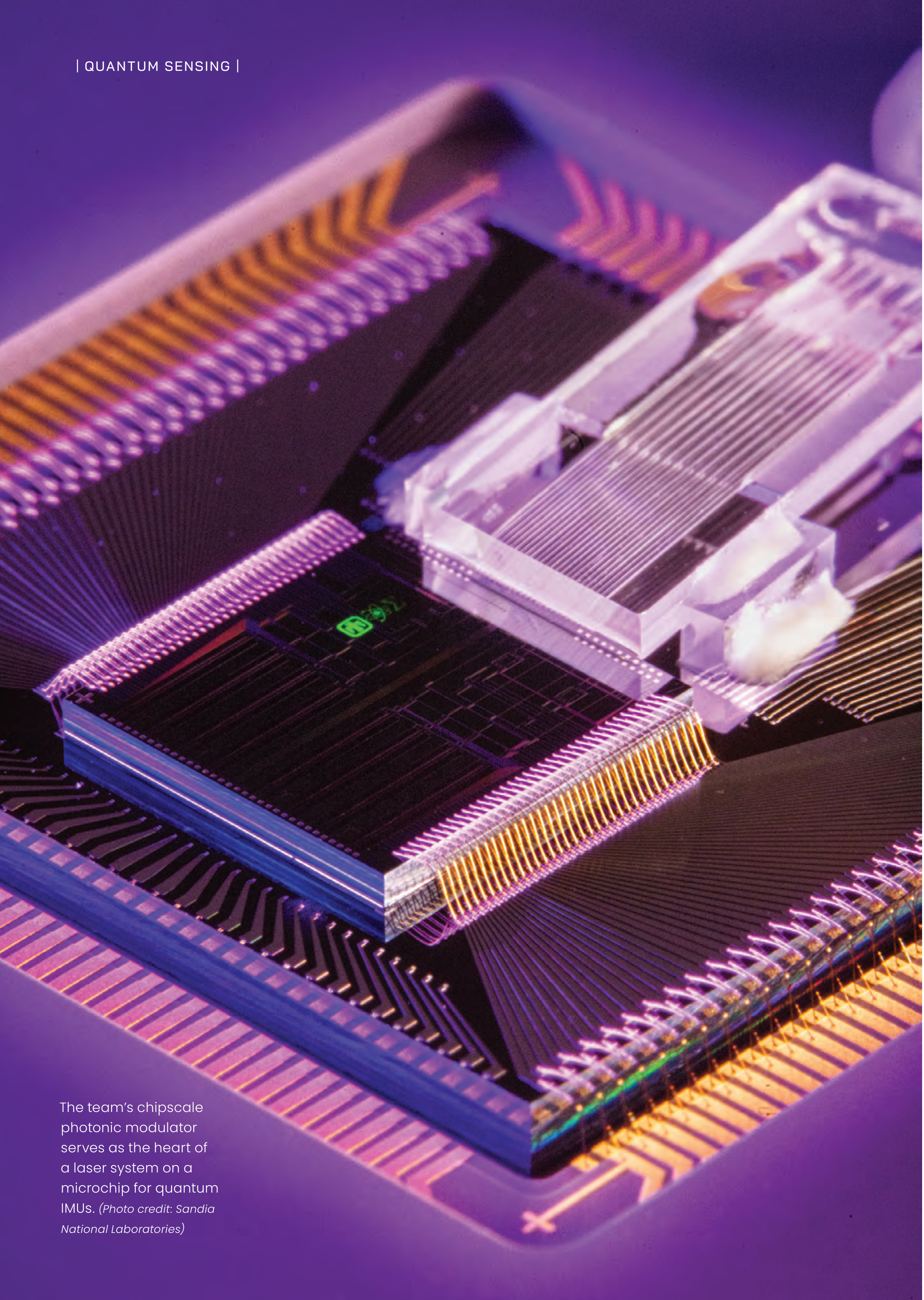
Schematic of the group's metasurface with a glucose layer.
(Image credit: Ahmed Jaber)

While there's been early research into the field of polaritonic chemistry, it's still new. Its potential is tremendous because polaritons can create entirely new degrees of freedom for chemistry. And the timeline for related applications is likely more than five years out, but based on growing interest of the scientific community it may at least end up being less than 10 years.

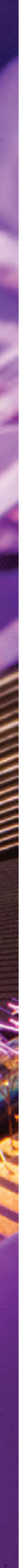
"The next step is to apply our design methodology of polaritonic devices for THz optical frequencies toward fundamental physics applications," says Ménard. "This includes, for example, exploring the modification of chemical reaction rates, properties like electrical conductivity, or temperature-induced phase transitions within materials."

FURTHER READING

A. Jaber et al., *Nat. Commun.*, 15, 4427 (2024); https://doi.org/10.1038/s41467-024-48764-6.



The team's chipscale photonic modulator serves as the heart of a laser system on a microchip for quantum IMUs. *(Photo credit: Sandia National Laboratories)*



Silicon photonic microchip components enable quantum sensing

Scientists create a chipscale photonic modulator to control light on a microchip and perform cold-atom interferometry with it.

SALLY COLE JOHNSON, EDITOR IN CHIEF

In an impressive step away from relying solely upon global positioning system (GPS) satellites for navigation, scientists at Sandia National Laboratories developed a multichannel silicon photonic modulator chip. It's part of a laser system designed for cold-atom interferometry—a form of quantum sensing to measure acceleration and angular velocity—and was created at the National Security Photonics Center.

Their device is an ultraprecise quantum inertial measurement unit (IMU) option wherever GPS is unavailable or for situations when satellite signals are intentionally denied or jammed.

This is an evolving national security risk within war zones, and motion sensors are advancing at a rapid rate now—dramatically shrinking in size and cost, while increasing in capability. Until recently, this type of sensor would have filled a large truck and cost significantly more. Shrinking bulky, expensive sensor components to fit on silicon photonic chips also drives down their cost.

And, thanks to the principles of quantum mechanics, quantum IMUs now offer unparalleled accuracy measuring acceleration and angular velocity—which enables ultraprecise navigation.

"The necessity of compact and rugged laser systems in configuring various quantum sensors inspires my work within this field," says Jongmin Lee, the Sandia scientist who led this work. "In particular, cold-atom interferometry relies on sophisticated and often bulky laser systems that limit the size, weight, and power consumption of quantum sensors. The challenge of miniaturizing and ruggedizing these laser systems is crucial for developing deployable quantum gravity and inertial sensors based on atom interferometry."

Chipscale photonic modulator design

An atom interferometer sensor system typically fills a small room—they're not known for being small—and a complete quantum IMU requires six atom interferometers.

Lee and his team set out to find ways to reduce the size, weight, and power needs of atom interferometers. They ended up creating a tiny photonic chip (8 mm × 8 mm), including four single-sideband modulators with custom features, which serves as the heart of a laser system on a microchip—and replaces a refrigerator-sized conventional laser system.

Four of these modulators are necessary to shift the frequency of a single laser to perform different functions. But a big downside of modulators is they tend to generate unwanted echoes, a.k.a. sidebands, which must be mitigated. To outmaneuver it, Lee and colleagues designed a suppressed-carrier, single-sideband modulator that reduces these sidebands by 47.8 decibels (also applicable to light intensity) and provides a nearly 100,000-fold drop.

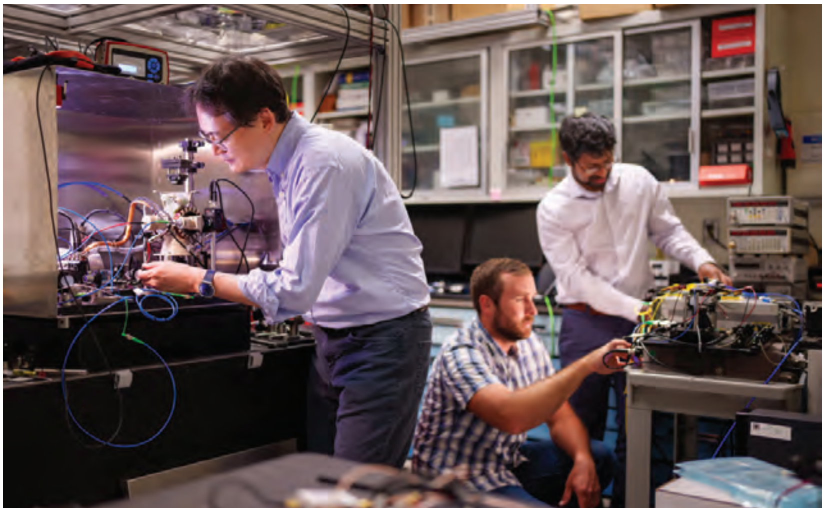
Importantly, they can be fabricated using the same process as computer chips. The team can make hundreds of their modulators on one 8-inch wafer, or more on a 12-inch wafer, which significantly reduces their cost.

PIC laser system architecture

The Sandia scientists' photonic integrated circuit (PIC) laser system architecture begins with a single telecom laser—because it has a longer lifetime and narrower linewidth than 780-nm distributed Bragg reflector lasers or distributed-feedback lasers—locked to an atomic transition, which creates multiple coherent light beams through single-sideband modulators.

The architecture of this laser system "is divided into three functional blocks: light modulation, optical amplification, and frequency doubling—from 1560 nm to 780 nm—for rubidium atoms," explains Lee.

Cold-atom interferometry requires cold-atom generation, state-selective atom detection, and a light-pulse sequence for matter-wave interference. "This process involves several key components: cooling, repumping, depumping, detection, and two Raman beams," Lee says. "The amplitude and frequency of each beam must be precisely controlled in a timed sequence. Most of the complex and costly light modulation tasks can be managed using a multichannel silicon photonic single-sideband modulator chip, which includes custom features."



Sandia National Laboratories' Scientist Jongmin Lee (left) prepares a rubidium cold-atom cell for an atom interferometry experiment while Scientists Ashok Kodigala (right) and Michael Gehl initialize the controls for a packaged single-sideband modulator chip. *(Image credit: Craig Fritz/Sandia National Laboratories)*

The size, weight, power consumption, and cost of conventional tabletop laser systems "limit the deployability of quantum sensors," Lee says. "Quantum inertial measurement units, multi-axis gravimeters, and multi-axis gravity gradiometers, in particular, require multiple laser systems."

Sandia's PIC laser system architecture can miniaturize and ruggedize the laser systems for cold-atom interferometry by leveraging silicon photonics that rely on the same complementary metal-oxide semiconductor (CMOS) fabrication process extensively used for microchips. This approach "enables mass production with a high yield rate, which ultimately reduces the cost of these quantum sensors and accelerates the development of field-deployable quantum sensors," Lee says.

Remaining challenges ahead include achieving low-loss optical packaging between a fiber array and a photonic chip, as well as performing low-loss photonic wire bonding between various integrated photonic chips. "We're also focused on demonstrating high-performance quantum sensors using a fully functional PIC laser system," says Lee. "Beyond this, we're exploring the optimal methods to operate quantum gravity and inertial sensors under conditions of vibrations and high dynamics."

Most surprising aspect of this work? "This work is a result of a multidisciplinary collaboration between the physics team and the photonics team," Lee points out. "Understanding both fields to design, implement, and test the PIC laser system for atom interferometry was quite challenging. One of the most rewarding moments was successfully demonstrating a proof-of-concept quantum sensor in the laboratory—it was an exhilarating experience that validated our efforts and highlighted the potential of our approach."

Quantum sensors and laser-based sensing ahead

As far as applications, the multichannel silicon photonic single-sideband modulator chip developed at Sandia can be widely applied to various quantum sensors and laser-based sensing technologies. "We're continuing to advance this technology within the given time and budget constraints, and we expect it to be ready for real-world applications within the next five to 10 years," says Lee.

Beyond navigation, Lee sees potential for their optical components, including the modulator, for LiDAR, quantum computing, and optical communications applications.

The Sandia team is now exploring various PIC technologies, including silicon photonics, III-V photonics, nonlinear optics, and MEMS-based photonics. "Through multidisciplinary collaborations, we aim to identify the best PIC solutions for specific quantum applications," Lee adds. "Also, we plan to provide quantum sensing testbeds through the Quantum New Mexico Institute for academia and industry—to enable other researchers to test their PIC laser systems with our testbeds."

FURTHER READING

A. Kodigala et al., *Sci. Adv.*, 10, eade4454 (2024); https://doi.org/10.1126/sciadv.ade4454.

LUNA

Advancing The Quantum Revolution 2.0

At Luna Innovations, we are at the forefront of the Quantum Revolution 2.0, enabling customers and industry leaders with products to advance quantum technology development.

Our comprehensive solutions cover:

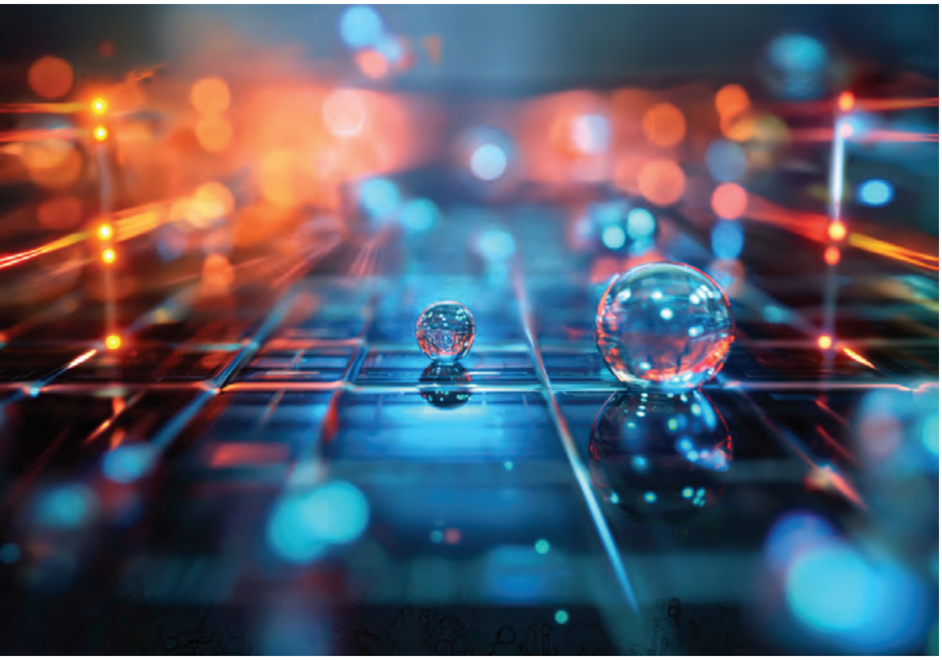
- Advanced Testing and Measurement Instruments
- Custom Subsystems and Interferometers
- OEM Photonics Modules and Lasers

Quantum Sensors/Metrology

Quantum Communications

Photonics Quantum Computing & Simulation

For more information on Luna’s Quantum Revolution 2.0, check out our wesbsite: www.lunainc.com/quantum-revolution



ID 327268785 © Irochka | Dreamstime.com

NSF $20M grant funds National Quantum Nanofab at CU Boulder

In this Q&A, Scott Diddams, a professor in the University of Colorado (CU) Boulder's Department of Electrical, Computer and Energy Engineering, shares his plans for the National Quantum Nanofab (NQN) "maker space."

LASER FOCUS WORLD STAFF

A $20M award from the U.S. National Science Foundation (NSF) will help create a nanoscale fabrication facility at the University of Colorado Boulder to enable quantum device fabrication, characterization, and packaging essential to advancing quantum applications—ranging from quantum computers and networks to atomic clocks and advanced quantum sensors.

Laser Focus World: **How do you start pulling together a project like the National Quantum Nanofab?**

Diddams: The key is the community around us—we have an amazing and diverse group of people in Boulder who are working on quantum devices, primarily focused on atoms, ions, and photons. This community is driving the need for new fabrication tools and the ability to build new quantum devices, aspects of which we don't fully know how to build yet. It's an interesting state between fundamental research and trying to figure out what an actual quantum chip or sensor will look like. But one thing is clear—we need new capabilities and infrastructure to fabricate quantum devices. So this is really what's driving it. Once we got the team together, we figured out which tools and capabilities we will need.

LFW: **Are you envisioning a quantum maker space?**

Diddams: A quantum maker space sums it up quite well. I also like to say it's a quantum machine shop for the 21st century. The idea of a maker space is that you can come here to build quantum chips or the basis of quantum devices for computing, sensing, or communications. It's really a place for a wide range of people—faculty, students, government collaborators, and the industry—who are starting to build quantum devices. We hope our tools and resources become so good we draw people in from outside Colorado. We want people to know there's something unique they can do or learn here or come create themselves.

LFW: **Is $20M enough to get going?**

Diddams: Yes, it's enough to make a big step forward. We're very grateful to the U.S. NSF for this funding. NSF is focused on providing funds for infrastructure because they recognize that while scientists, faculty, and people within the industry have ideas about quantum devices, being able to realize them often gets held up by infrastructure. This $20M grant puts us in a great position to have an impact.

LFW: **Is there a fab onsite at CU already?**

Diddams: The University of Colorado has nanofab facilities. What makes the new NQN different are the people who will be involved. There is an analogy to a more conventional machine shop, where you would find very similar tools on the surface—drill press, a lathe, a milling machine. What makes it unique are the people who operate these tools and have a vision of what you can do with them. Our nanofab will be unique not just because of the tools, but also because of the people operating and using them.

LFW: **What types of tools do you plan to have at the NQN?**

Diddams: Many of the tools will be those used for lithography, patterning, etching, and bonding. Quantum is intrinsically small, and many of the devices we envision will have nanoscale features. If you want to build quantum devices or chips, they require materials and combinations of materials that are different than silicon we use for integrated circuits today. So we will need tools that can process different materials and put them together in new ways to operate in challenging environments like high vacuum or cryogenic temperatures.

LFW: **What types of training do you plan to offer?**

Diddams: The NQN is really coming up at the right time—there's a big parallel effort in our country with the CHIPS Act that is reinvigorating tools and technologies for integrated circuits, and all kinds of different chips and their fabrication. There's a big demand now as companies move to invest in new manufacturing plants or facilities within the U.S. to train people to work there. We plan to offer development classes and opportunities for undergrads or grad students to work on nanofabrication tools so they can learn to make basic quantum devices—it will be super important for the future workforce to know how to do this.

LFW: **For people into lasers, optics, and photonics, what's the coolest thing going on at NQN?**

Diddams: It's nanophotonics. If you go to a lab now and, for example, look at an advanced optical clock—the best time-keeping pieces humans have ever made are quantum-based optical clocks—it's usually spread out over a big board and its optomechanical mirrors and mirror mounts are essentially a one-off work of art.

Thinking to the future of similarly powerful quantum devices, we might ask: Can I imagine making this simpler and more robust, or perhaps a path to easily and repeatedly manufacture this? For it to be possible, we need integrated photonics. Lasers and photonics touch so many areas of quantum, and sometimes the qubit is a photon or an atom. In most cases, you are going to need the laser and laser light to address, prepare, or communicate between different qubits. This makes integrated photonic devices fabricated at the chipscale even more important going forward, and that will be a big part of the work that goes on at NQN as well.

LFW: **Personal favorite cool thing about quantum stuff?**

Diddams: Through the manipulation of quantum states of light, we can make better measurements. I've spent a lot of my career developing laser tools for the most demanding types of measurements, and understanding, engineering, and measuring quantum light allows me to make these measurements even more precise.

LFW: **What's the timeframe to build the NQN?**

Diddams: It's a five-year grant from NSF. The NQN will be complex to construct because it requires tight tolerances on temperature, air handling, and vibrations. It needs to be built carefully to ensure the tools work right. Even then, I hope we can do some things early—within a few years, we might be able to start getting students in for training opportunities.

Spin center arrays serve as analog quantum simulators

A chain of quantum magnetic objects, a.k.a. spin centers, can simulate a variety of magnetic phases of matter and the transitions between these phases.

TROY LOSEY AND **SHAN-WEN TSAI**

Quantum simulation is a powerful tool that can realize Hamiltonians—an operator that corresponds to the total energy of the system—that contain impactful physics but may not occur naturally. Analog quantum simulators are physical systems that are relatively easy to control, such that the Hamiltonians realized by the simulators have many tunable parameters that allow for the simulation of a wide variety of models within a wide range of parameter space. Furthermore, these simulators can be experimentally probed to study the models further or even potentially be made into devices that exploit the phenomena that arises within the models for practical purposes.

Due to the exponentially increasing degrees of freedom with respect to the size of quantum systems, quantum simulators are better suited to study many aspects of quantum systems than classical computers. We and our collaborators propose a solid-state analog quantum simulator for the study of critical floating phases and commensurate to incommensurate phase transitions.[1]

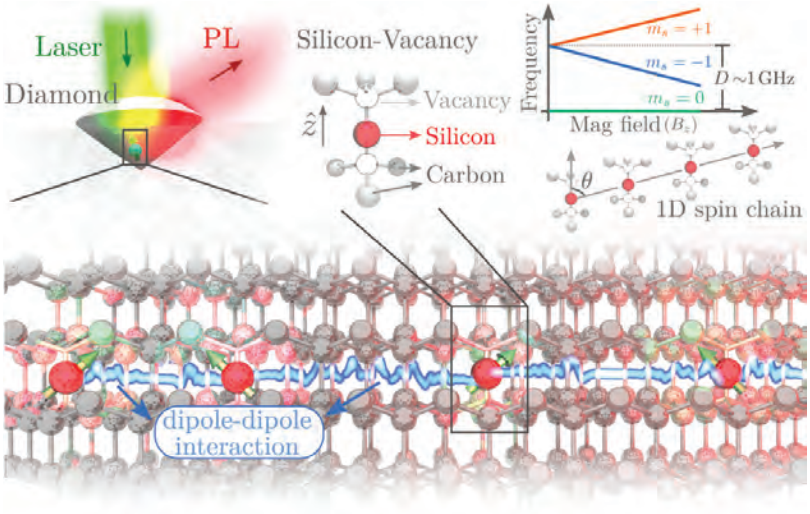
Solid-state quantum simulator

Our proposed quantum simulator is a one-dimensional chain of anisotropic S=1 spin centers that interact through the magnetic dipole-dipole interaction and are implanted into a crystal.

Spin centers are defects that can be placed in a crystal and due to their unique electronic properties, they behave as localized spins. They can be initialized and read out by lasers, and are well known for having long coherence times that persist even at room temperature.

While NV^- spin centers have been widely studied as sensors and high-temperature qubits, the dipolar interaction is relatively weak, so we propose spin center candidates without hyperfine splittings, such as the silicon vacancy center (SiV^0) in diamond or divacancies in silicon carbide (SiC). Unwanted hyperfine interactions between spin centers and nuclei within the crystal can also be avoided by using isotopically pure crystals where the atoms have zero nuclear spin. Isotopically pure diamond and SiC can feasibly be grown with ^{12}C and ^{28}Si for this purpose.We were initially interested in using S=1 spin centers to simulate lattice gauge theories that are of interest in high-energy physics, but we encountered a roadblock because the dipolar coupling is dominated by the spin centers' anisotropic Hamiltonian term. However, we quickly found that a new avenue had opened where an external magnetic field can be applied to make the spin centers have a two-fold nearly degenerate ground state,

Shan-Wen Tsai (left) and Troy Losey. *(Photo credit: University of California Riverside)* causing them to behave as $S=1/2$ particles on the energy scale of the dipolar interaction. This makes it possible to simulate a variety of $S=1/2$ phases and critical behaviors with spin centers. Notably, this includes floating phases, which in this case are incommensurate spin density waves, and quantum phase transitions such as a line of transverse-field Ising transitions and Berezinskii-Kosterlitz-Thouless and Pokrovsky-Talapov points. These phases and transitions can be controlled via external magnetic fields and varying the orientation of the spin center chain within the crystal.



Depiction of a silicon vacancy in diamond and the corresponding spin array of SiV centers coupled through dipole-dipole interaction. Spin centers are initialized by laser light and optically read through the emitted photoluminescence (PL). The energy levels of different spin projections along the z-direction are modified by the magnetic field (B_z), and the resulting Hamiltonian depends on B_z and the angle θ between the z axis and the direction of the spin center array.

While there has been interest in quantum simulating floating phases and commensurate-incommensurate transitions, and there have been proposals and experiments to do so via ultracold atom quantum simulators, such as Rydberg atom arrays, this is the first proposal to realize these behaviors in a solid-state quantum simulator.

With current techniques, this quantum simulator is difficult to experimentally achieve. It requires spin centers to be precisely implanted, with even spacing at about 5 to 10 nm. This maximizes the dipolar interaction while the spin exchange interaction remains negligible. While some groups are closing in on being able to implant spin centers with near 10-nm separations, it will require more work to build a chain long enough and evenly spaced enough to realize the physics that we expect from this system.

It is worth noting, however, that spin-center-based qubits are a leading candidate for room-temperature quantum computing, and improving upon techniques to precisely implant nearby spin centers is necessary for this milestone. Another complication is that due to the weak nature of the dipolar coupling between spin centers, this simulator is expected to operate at temperatures near and below 10 μK. This low temperature regime is currently unreachable in experimental settings. Furthermore, it is difficult to initialize and read out information from spin centers placed so closely together.

While these experimental challenges limit the utility of this quantum simulator in the present, we are able to address these challenges for future spin-center-based quantum simulators by considering stronger and longer-ranged interactions between spin centers. There are promising proposals to engineer spin-spin interactions between spin centers with these qualities by using bosonic modes as mediators.[2,3] Moreover, it is predicted spin centers will still have very long coherence times even after introducing bosonic modes to the system.

Considering different interactions between spin centers and more complicated geometries of spin center arrays than a straight one-dimensional chain will provide a lot of versatility for Hamiltonians that can be simulated. For example, higher-dimensional arrays of spin centers could be a promising platform for the study of spin dynamics such as spintronics, which takes advantage of spin degrees of freedom to store and transfer information remarkably efficiently, and topological solitons, which are of high interest across many fields of physics.

As we have shown, there is great potential for spin-center-based quantum simulators to simulate impactful physics and have avenues available to address experimental limitations. We believe there is a promising future for spin-center-based quantum simulators.

REFERENCES

1. T. Losey et al., *Phys. Rev. B*, 110, 014413 (2024). 2. D. R. Candido, G. D. Fuchs, E. Johnston-Halperin, and M. E. Flatté, *Mater. Quantum. Technol.*, 1, 011001 (2021). 3. M. Fukami, D. R. Candido, D. D. Awschalom, and M. E. Flatté, *PRX Quantum*, 2, 040314 (2021).

Troy Losey is a graduate student and **Shan-Wen Tsai** is a professor of physics and astronomy, both at the University of California Riverside; www.physics.ucr.edu.

Can topology help transmit and process quantum information?

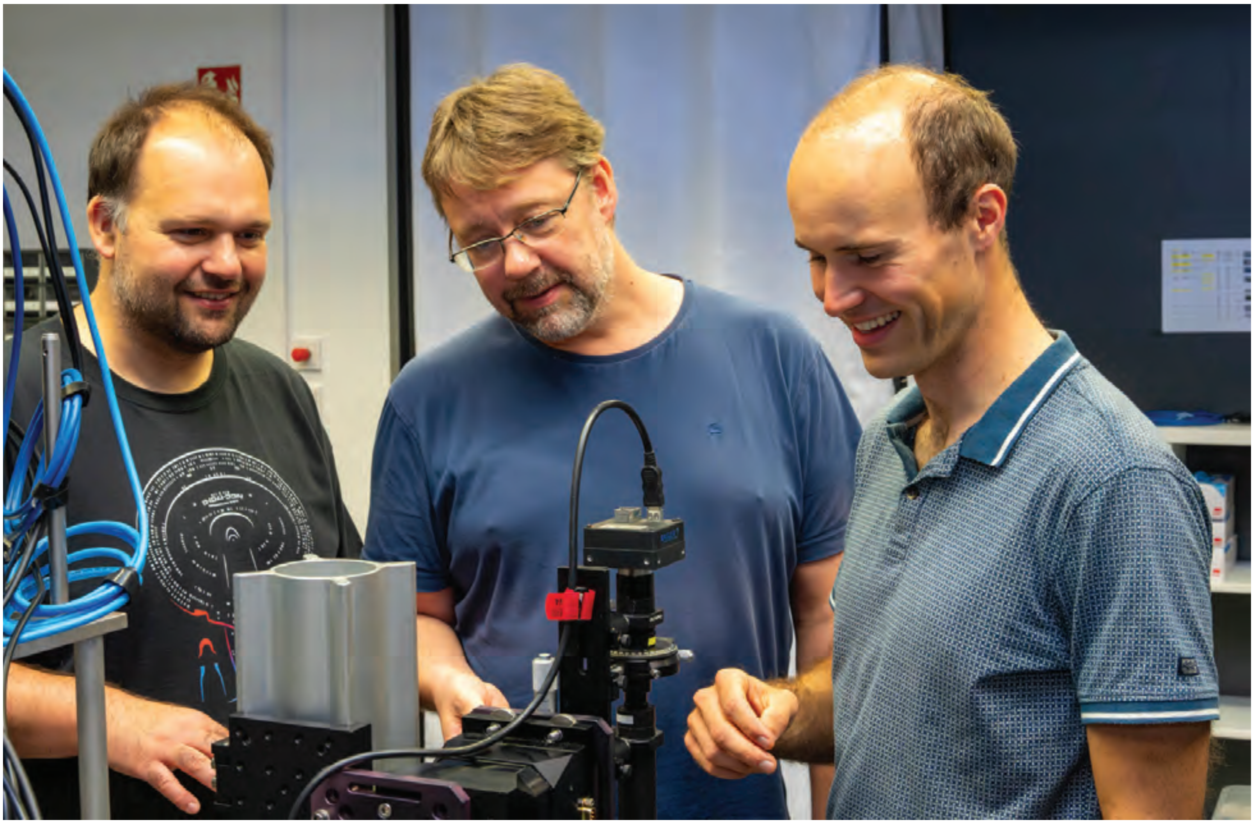
Yes—although topology is commonly perceived as a single particle or "classical" phenomenon, it's also valid within the quantum realm and may play a big role in quantum computing.

SALLY COLE JOHNSON, EDITOR IN CHIEF

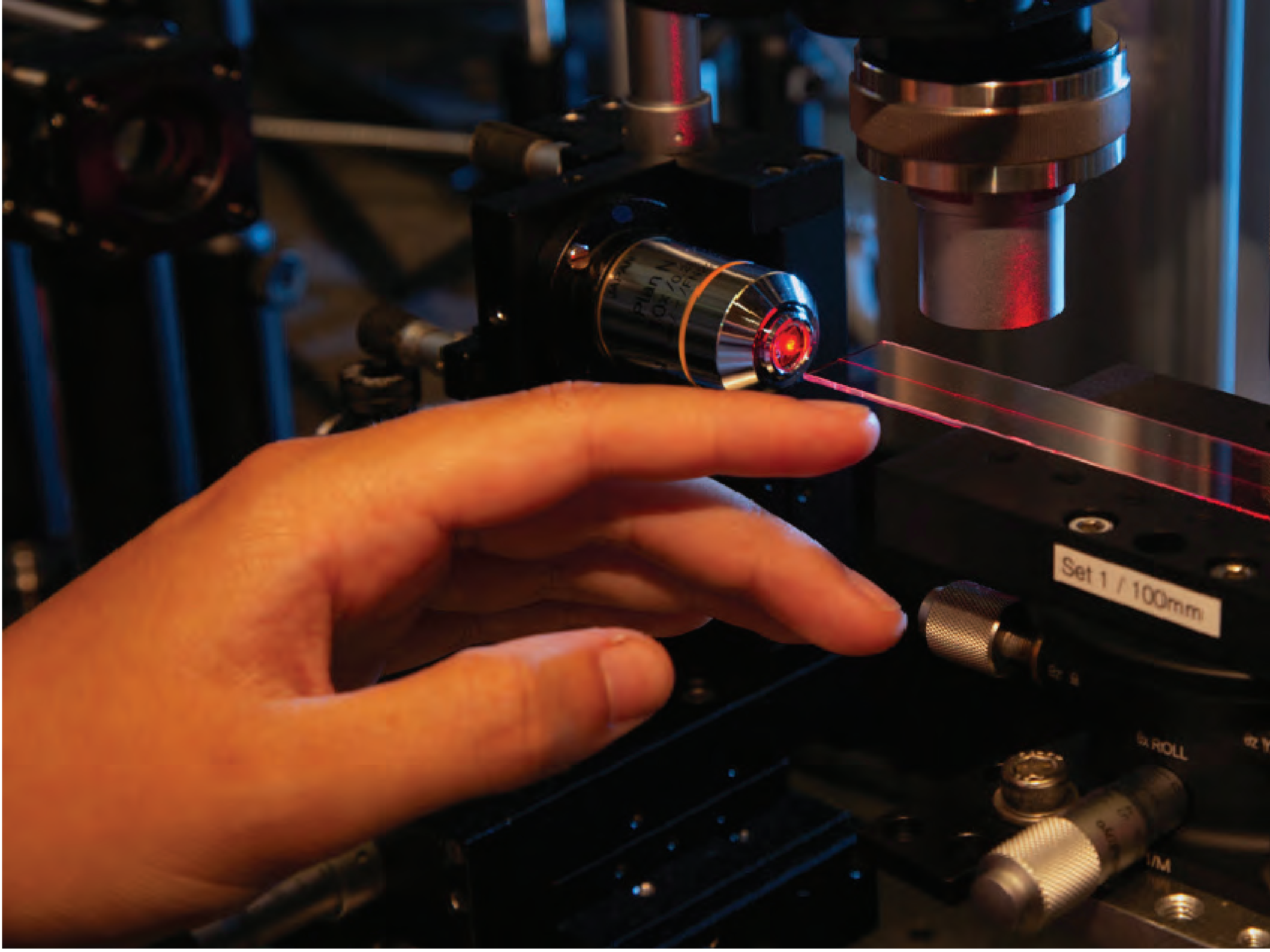
A group of researchers led by Alexander Szameit, a physics professor at the University of Rostock in Germany, paired the topologically robust properties of light with the interference of photon pairs. And they discovered topology—an abstract mathematical concept initially developed to classify solid geometries by their global properties—is also valid within the quantum realm.

Light follows the global characteristics of the waveguide system within topological systems. Even perturbations to the waveguides such as defects, vacancies, and disorder won't divert its path.

This work, which was a collaboration with colleagues from the Albert Ludwig University of Freiburg, opens numerous intriguing questions involving topological robustness of entanglement and even nonlocal topological effects. It's a big deal because topology may soon play a



Matthias Heinrich (left), Alexander Szameit (center), and Max Ehrhardt (right). *(Photo credit: University of Rostock)*



key role in the transmission and processing of quantum information.

Szameit's group explores integrated photonic waveguide circuits and quantum light. "Originally, we used classical light for quantum simulations of solid-state phenomena," he says. "But we realized there's much to be discovered by extending our research to the quantum features of light, such as entanglement and nonlocality. This is when it started, out of curiosity, 12 years ago. Everyone should remember the name of Max Ehrhardt, my Ph.D. student who did the work, because he has a truly ingenious mind."

Hong-Ou-Mandel interference meets topological photonics

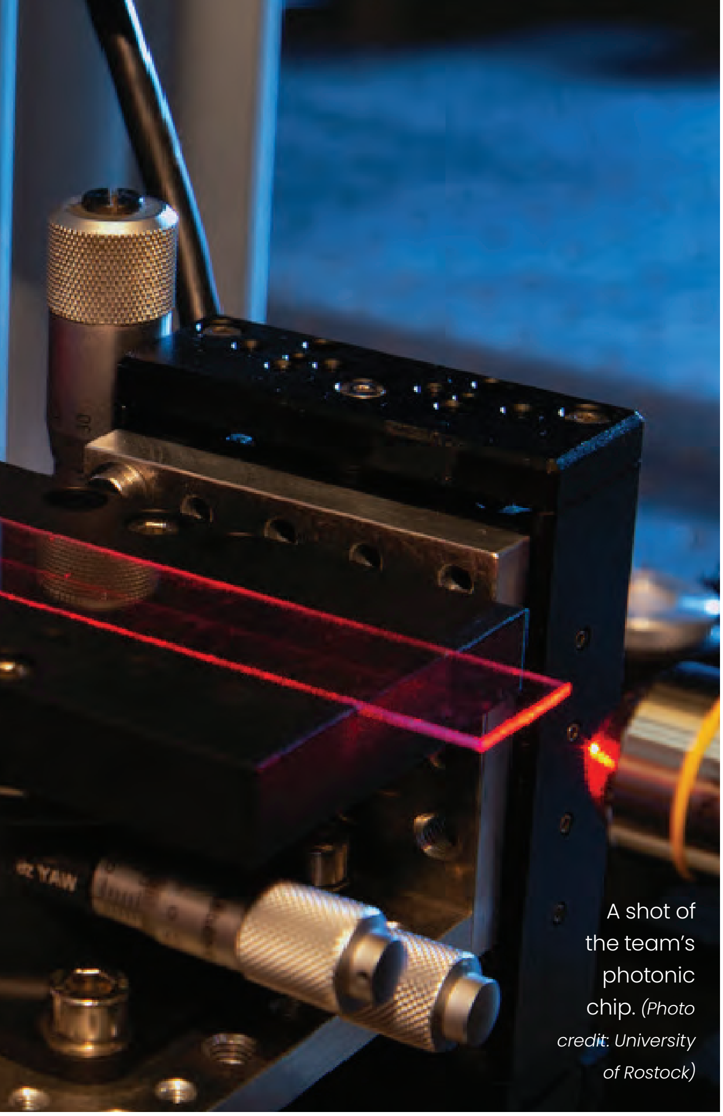
The quantum effect the team's experiment is based on is Hong-Ou-Mandel interference. In 1987, the three physicists observed the behavior of photon pairs within a beam splitter during an experiment and found that a photon, which interferes with itself due to its behavior as an electromagnetic wave, can also form interference patterns with other light particles. Beyond entanglement as a fundamental feature of quantum light particles, this groundbreaking discovery is an ingredient for optical quantum technologies, including quantum computers.

"Two indistinguishable photons enter a network and bunch up," explains Szameit. "When they enter a beam splitter from different sides they will always exit it together—although we can't tell which side of the beam splitter the pair will exit. This effect is rather fragile: the splitter requires a perfect 50/50 splitting ratio, and any deviation immediately results in a degradation of the bunching."

Topological photonics is another topic Szameit and colleagues have focused on for 10 years. "By using topological concepts, we can generate light waves that are robust to distortions, which means they can travel even around corners and defects," he says. "Our idea was to combine both effects to get topologically protected Hong-Ou-Mandel interference."

Design work: An artificial dimension

To implement this idea, the team turned to an artificial dimension. "We used the polarization degree of freedom of light," says Szameit. "It allows us to implement a



A shot of the team's photonic chip. *(Photo credit: University of Rostock)*

three-dimensional (3D) system, although the waveguide circuit has only two dimensions (width and length). Height is emulated by the polarization. It's a very general concept, but such 'synthetic dimensions' allow us to go beyond the constraint of only three spatial dimensions."

The biggest step toward their findings "was the development of a synthetic polarization dimension in waveguide circuits," Szameit says. "As we became more experienced, we discovered the features of this synthetic dimension allow us to implement various photonic systems by judiciously tailoring this birefringence of each waveguide."

Among the features, the team found photons can behave as if they are affected by a gauge field with quantized magnitude, which is established by topology within the synthetic polarization dimension. "It was the breakthrough we needed to implement topologically protected quantum interference," Szameit says.

The researchers were seriously impressed by the level of robustness of quantum interference introduced when they implemented topological protection. "We couldn't believe it when we saw it in the measurements: but even when we had very strong deviations from the ideal beam splitter, we were still able to observe the quantum interference almost undisturbed," says Szameit. "In conventional beam splitters, quantum interference would have vanished completely. It was only when we did the calculations that we realized that topology is an incredibly big gain here."

Ehrhardt adds that topological protection of optical elements is a design tool necessary to ensure proper operation. He likens the odd behavior of the quantum nature of light when pairs of photons see each other to them perceiving the waveguide structure as twisted. And this photon pair ends up dancing along the twisted dancefloor as a couple.

"Photons that pass through the waveguide separately experience a conventional flat surface, so we have a topological difference," Ehrhardt says.

Quantum interference applications ahead

Topologically protected Hong-Ou-Mandel interference can be used for any applications in which quantum interference is useful. "In particular, Hong-Ou-Mandel interference gives rise to ultraprecise measurements," Szameit points out. "Time measurements, for instance, achieve attosecond precision, so a more reliable interference method might be able to boost the precision to another level."

Another potential application is to generate and process quantum states for quantum computing. Quantum computers use "a large number of beam splitters to accomplish quantum interference so that small inaccuracies of the individual beam splitters are strongly reflected in the final result," Szameit adds. "In this regard, topological protection of the Hong-Ou-Mandel interference will reduce the inaccuracies, which allows for bigger quantum circuits without compromising functionality. Eventually, it will bring us one step closer to a photonic quantum computer."

What's next? "New questions arose from our observation," says Szameit. "First, are there other quantum effects that can benefit from the topological features of the synthetic polarization dimension? Can we establish similar topological features in other photonic synthetic dimensions such as frequency or orbital angular momentum of light? And, finally, can we find other stable topological effects of more than two photons if we use the topological features available in the synthetic polarization dimension?"

FURTHER READING

M. Ehrhardt, C. Dittel, M. Heinrich, and A. Szameit, *Science*, 384, 1340–1344 (2024); doi:10.1126/science.ado8192.

Quantum world, meet Chromacity Ltd.

In this Q&A with Chromacity CEO Julian Hayes, he introduces us to the company, and it'll be nearly impossible for anyone to ever top his company fun facts.

LASER FOCUS WORLD STAFF

Photo credit: Chromacity Ltd.

Julian Hayes, CEO of Chromacity Ltd.

Laser Focus World: **Can you introduce us to Chromacity?**

Julian Hayes: Chromacity was a spin-out from The Institute of Photonics and Quantum Sciences (IPAQS), part of Heriot-Watt University in Edinburgh, U.K. Formed in 2012, IPAQS undertakes world-leading research in photonic physics, engineering photonics, and quantum sciences. The Ultrafast Optics Group, led by Professor Derryck Reid, is a pioneer in the development of tunable nonlinear infrared optical parametric oscillators (OPO).

The team consisting of Professor Reid and Dr. Carl Farrell had developed a novel and patented ultra-high-efficiency oscillator core for its tunable infrared OPO. Seeing an emerging market opportunity for tunable infrared ultrafast OPOs across a wide range of research activities, Professor Reid, Dr. Farrell, and fellow researcher Dr. Christopher Leburn formed Chromacity in 2013.

Chromacity Ltd. manufactures both fixed-wavelength infrared femtosecond fiber lasers and picosecond optical parametric oscillator (OPO)-based tunable infrared laser systems. They are used principally for scientific and industrial research, including spectroscopy (materials analysis), microscopy (biological imaging), defect detection, pollution monitoring, and a broad variety of quantum applications.

LFW: **What types of lasers are you offering for quantum work?**

Hayes: Chromacity's lasers are used across the quantum space. The ability to generate and detect quantum states of light using entangled photons is a rapidly expanding research area in the development of next-generation secure communications, both for guided wave and free-space systems. Our 1040 ultrafast femtosecond laser is an important tool used to create entangled photons via spontaneous parametric downconversion in nonlinear crystals.

Single-photon light detection using superconducting nanowire single-photon detectors (SNSPDs) is a frontier technology for quantum optics and optical quantum applications. SNSPDs that operate in the mid-infrared offer the potential of improved performance for quantum sensing, LiDAR, and deep space communications. The Chromacity ultrafast OPO lasers are an ideal match, offering the opportunity for researchers to test the sensitivity and temporal characteristics of the latest-generation mid-infrared SNSPDs.

Our lasers are an essential element of research into hyperspectral quantum imaging systems, using quantum-correlated beams. This technique uses correlated signal and idler photons created by a high peak power pulsed laser like the Chromacity 1040 to image through lossy scattering media, such as biological systems or objects embedded in other materials.

LFW: **What kinds of applications are your lasers enabling?**

Hayes: Biological imaging modalities such as two-photon microscopy or second-harmonic generation imaging require surprisingly high-intensity laser excitation, typically exceeding 40- to 50-kW peak power. However, this level of power is easily delivered by today's advanced ultrafast lasers with ultrashort pulse-generating capability.

Increasingly, potential users are migrating to more robust, smaller, more power-efficient, and significantly lower-cost femtosecond-pulse fiber laser solutions like the Chromacity 1040 and 920. These compact desktop patented fiber lasers deliver ultrastable long-term performance with optimal pulse quality for high-contrast imaging performance and are rapidly replacing traditional high-power water-cooled Ti:sapphire lasers.

Chromacity's tunable infrared lasers are enabling a step change in capability for open-path pollution measurement, helping to deliver real-time, in-the-field measurement of greenhouse gases (CO_2, N_2O, CH_4), ammonia, and other atmospheric pollutants. Traditional techniques are slow and require physical sampling of the gases, leading to contamination of the instrument and inability to measure remote sites. Chromacity's tunable bright infrared laser beam offers the potential for unprecedented insight of wetland/estuarine areas, landfill sites, or any industrial site, and can be used within emerging sectors in the drive to net-zero, such as the large-scale use of ammonia as an energy carrier.

LFW: **Fun fact about the company?**
Hayes: Chromacity is a Scottish company, embedded within the Edinburgh photonics community. But at its core is a group of engineers from the Shetland Islands. The Shetland Islands is an archipelago off the northern coast of the U.K., on the same latitude as parts of Alaska. It was occupied by the Vikings and ruled by Norway until the 15th century, when it was pawned to Scotland in lieu of a dowry. It is also the windiest place in the U.K., recording an annual average wind speed of 7.5 m/s. Uniquely, it has 55 lighthouses, which is why Chromacity names its lasers after lighthouses. The Viking heritage is still very strong, which is why you'll find members of the team nurturing beards in the autumn for the annual Up Helly Aa winter fire festival.

LFW: **Are you seeing anything interesting emerge within the quantum realm right now?**
Hayes: The recent announcement by the U.K. government of a £160M (~$178M) investment in the creation of five quantum hubs, and the Netherlands' Quantum Delta NL program are exemplars for governments and industry working together to create a vibrant ecosystem for quantum technology development and exploitation. The challenge for everyone is to bridge the gap between fundamental research and practical solutions. In some areas, being able to create a commercial product seems a long way off. However, there are signs a few quantum technologies are beginning to see the light of day. Quantum key distribution (QKD) systems used for communications networks are a production reality. And quantum spectroscopy looks like it is on the verge of generating a step-change in capability compared to existing systems, and with real-world practicality. Governments and, more importantly, investors will need to see more successes if the current high level of investment in quantum technologies is to be maintained.

> Chromacity's lasers are used across the quantum space.

Expanding quantum technology capabilities

Exail, a global industrial company within the field of photonics and quantum technologies, was the first to commercialize industry-grade quantum gravity sensors. Its success in quantum sensing comes from development of cutting-edge technologies that are now accessible to a wider range of users, helping them bring quantum innovations to the market.

BRUNO DESRUELLE

Exail is one of the key European players within the field of photonics and is involved in specialty optical fibers, modulation solutions, ultra-stable fibered micro-optical benches, lasers, and quantum sensors. The company wants to empower photonics engineers worldwide with advanced optical technologies that have proven their relevance for many applications: laser, space, sensing, or quantum.

With a focus on innovation, risk-taking, and customer satisfaction, Exail develops advanced high-performance solutions. Meeting the quality and reliability standards required for demanding operations, these solutions are optimized for use in a wide variety of environments, from temperature-stabilized laboratories to deep space.

Bringing complex quantum experiments to industry-standard

As Eric Mounier, Yole Group, wrote in a previous issue of *Laser Focus World*'s *Quantum Innovators*: "Photonics will be of great importance to the development of quantum technologies." He adds that there are only a few suppliers of laser systems usable for quantum systems manipulation, but they are absolutely critical.

Exail is one of these suppliers, developing intelligent laser systems (ILS) and integrated micro-optical benches (iMOB). Developed for quantum sensing, they are now accessible to a wider audience with other optical solutions like polarizing fibers, phase and amplitude lithium niobate ($LiNbO_3$) electro-optic modulators at 800 nm, and laboratory laser modules.

Today, we support research labs, agencies, or companies in developing their quantum technologies with industry standards, whether they rely on neutral atoms, photons, or ions. Pasqal (quantum computing), WeLinq (quantum links), or ThinkQuantum (quantum communication) are examples of flagship

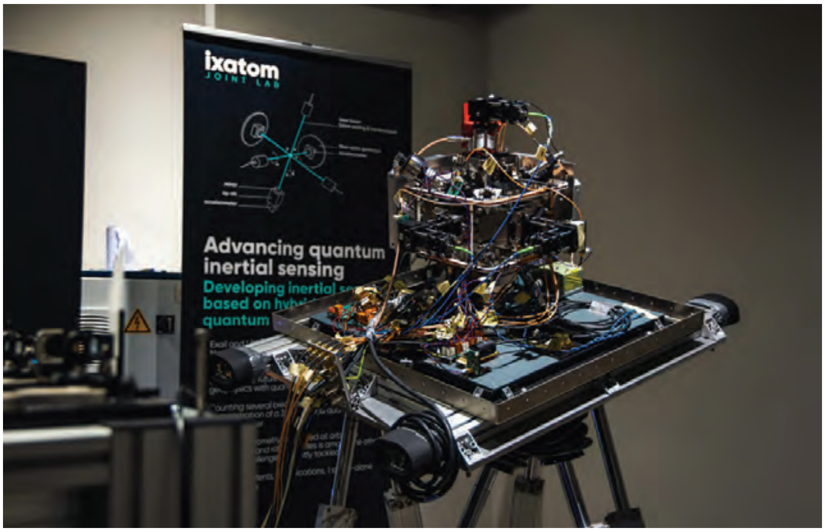
Deployed on the top of Mount Etna since 2020 by the Italian National Institute of Geophysics and Volcanology (INGV), Exail's Absolute Quantum Gravimeter has demonstrated its capability to detect minute gravity variations induced by magmatic activities. *(Photo credit: Exail)* startups that use our solutions to bring their quantum innovations to the market.

Pioneering cold-atom based quantum technologies

Exail's journey into quantum sensing began over a decade ago, inspired by Nobel laureate Alain Aspect's work. Muquans, a startup founded by Aspect's former students and colleagues, was acquired by Exail in 2021, and was the first to commercialize quantum sensors based on laser-cooled atoms. Today, nearly 20 of Exail's Absolute Quantum Gravimeters (AQG) are in operation worldwide. They are deployed for use in real-world applications like volcanology, geodesy, and hydrology, demonstrating the instrument's reliability.

Our AQG cools and traps rubidium atoms with lasers and performs a matter-wave interferometry sequence on the cloud of atoms to precisely measure its acceleration while it is free-falling under the effect of gravity. This is an absolute sensing method that leverages the quantum advantage. The gravimeter has a robust, user-friendly design—with a separate sensor head and laser source—to ensure accessibility even for nonspecialists. Full installation and remote support are assured throughout the equipment's lifetime.

We're now developing next-generation quantum gravimeters through research initiatives like Horizon Europe's FIQUgS project, aimed at creating an instrument capable of detecting underground objects such as water pipes and mines. Such an extreme sensitivity comes from the Differential Quantum Gravimeter's ability to simultaneously measure the absolute values of both gravity and its vertical gradient. Exail is also contributing to the CARIOQA program, led by the French and German space agencies (CNES and DLR), to develop a space-based quantum accelerometer for climate monitoring.



The hybrid rotating atom interferometer in the experiment room of iXAtom joint lab (France). *(Photo credit: Exail, G. Lemaintec)*

Shaping the future of inertial navigation and geophysics

Exail reinvests nearly 20% of its revenue into R&D. One key initiative is the iXAtom joint laboratory,[1] where we work with academic experts to push the boundaries of inertial sensing with hybrid classical-quantum technologies. A significant milestone was reached in 2022, with the demonstration of a 3-axis hybrid quantum accelerometer,[2] moving closer to developing a drift-free inertial navigation system that exploits the quantum advantage, which could completely overcome the need for external recalibrate using GNSS.

In 2024, iXAtom unveiled a high-performance quantum inertial sensor that combines cold-atom technology with fiber-optic gyroscopes.[3] The performance reached by this hybrid sensor under strong rotations and arbitrary orientations meets the operational requirements for diverse platforms, including submarines, aircraft, and spacecraft. The complete validation of this strapdown hybrid sensor could lead to absolute gravity mapping capability and would be a gamechanger in geodesy, to improve the most basic model of the Earth.

Fun fact about Exail

Since 2021, the LUMINA dosimeter, based on an optical fiber architecture manufactured by Exail in collaboration with CNES/Hubert Curien Laboratory/CERN, has been tested by astronauts Thomas Pesquet (FR) and Sultan Al Neyadi (UAE) for the active monitoring of radiation on-board the International Space Station (ISS).

REFERENCES

1. Joint laboratory between Exail and LP2N lab (CNRS/Institut d'Optique Graduate School/ Univ. Bordeaux)
2. S. Templier et al., *Sci. Adv.*, 8, 4 (2022).
3. Q. d'Armagnac de Castanet et al., *Nat. Commun.*, 15, 6406 (2024); https://doi.org/10.1038/s41467-024-50804-0.

Bruno Desruelle is the vice president of photonics at Exail, Saint-Germain en Laye, France; www.exail.com.

Electro-optic polymers are a potential enabler of quantum computing

How would Max Planck see the quantum world being enabled by electro-optic polymers?

MICHAEL LEBBY AND **JOHN ZYSKIND**

Max Planck (1858-1947) is recognized as a father of quantum technology. His work as a theoretical physicist and the discovery of energy quanta was recognized with a Nobel Prize in Physics (1918). While dedicating his life to theoretical physics, he is remembered most as an innovator of quantum theory and for his understanding of atomic and subatomic processes.

It would be interesting to have insight into what Planck would think about our world more than a century on from his pathbreaking work. Not only have we evolved beyond delivering post or mail using stamps and envelopes for communication, but we have created a social infrastructure that demands new technologies and solutions for challenging problems. These new technologies now need to look to quantum computing, quantum engineering, and quantum-based mechanics and technology, and use these tools to implement effective and enabling solutions to continue advancement of our society.

Perhaps Planck would be in the middle of this quantum revolution, helping us understand and implement quantum technology into products we can all benefit from. We wonder how excited Planck would be to work on a real quantum computer.

During the past few years, the unequalled potential of computing power is driving the interest and investment in quantum. This is not expected to wane in coming years, especially with the rise of generative artificial intelligence (GenAI) that demands ever-increasing computational processing. It also creates challenges both for electronic chip design and the optical interconnects that carry increased information flow within and around data centers.

While digital-based information flow today is required to upgrade speed and lower power consumption, quantum-computing-based information flow based on qubits has the potential to contain much more information than digital bits and enable massive computing power because of the way qubits interact and behave. Quantum computing using qubits can enable computing power far more than anything feasible with conventional digital computers now.

These tremendous capabilities are enabled by the unique properties of quantum mechanics and the way particles and photons interact under the laws of quantum mechanics. Interesting and strange effects such as superposition, interference, and entanglement can be leveraged

Three various types of organic chromophore-based polymers that are available commercially. *(Image credit: Lightwave Logic)* significantly. In today's environment, we are only scratching the surface of a field that is still in its infancy.

One of the enablers of digital computer networks, such as those within data centers, is the use of traditional digital optical modulators. These are devices that encode information on fiber- optic interconnects to enable increased data rates and information flow. Lightwave Logic is a Colorado-based company that sources and creates state-of-the-art organic materials for a class of electro-optic polymers (EOP) called Perkinamine that are used in optical modulator devices.

For optical modulators, the company starts with its own proprietary-designed organic chromophores, which are a key ingredient of polymers, and deposits them onto a silicon chip within standard silicon wafer fabs using standard tooling and equipment. While optical modulators enable headroom for increased data rates and lower power consumption today, EOPs' similarly high-performance metrics make it suitable for quantum computing.

EOPs are promising for quantum applications both because of their ability to manipulate the properties of photons that can be used for preparing quantum states for qubits and because of their low loss (for preserving the very small signal levels produced by quantum computers), very high EO coefficient (high sensitivity for the low signal levels involved), high radio-frequency (RF) bandwidth (for very short pulses that emanate from quantum computers), and the ability of EOPs to work at cryogenic temperatures to minimize thermal corruption of the qubit quantum states.

EOP materials can also be used as quantum transducers at the ingress and egress of a next-generation quantum computer converting between electron and photon pairs while preserving the quantum entanglement.

The use and functioning of qubits are based on the quantum behavior and interactions of single photons and/or particles or single photon pairs and/or electron pairs and maintaining the integrity of their quantum states, which are easily disturbed if they are not protected from thermal perturbations.

Quantum computers based on the quantum states of electrons, such as Josephson junctions, must be operated at extreme cryogenic temperatures (mK) because of the strong interactions of electrons with thermal perturbations. Those based on photons, for which interactions are not as strong, can be operated at somewhat higher cryogenic temperatures (several K).

By making as much of the system as possible photonic, which enables higher operating temperatures, the power requirements for refrigeration can be reduced to lessen the energy footprint. In view of this, the capability of EOPs to operate at cryogenic temperatures required for quantum computing and quantum transducers can be quite valuable for quantum applications.

Even when the quantum computing engine is based on the quantum states of electrons, such as Josephson junctions, the information must be extracted photonically because of the extreme sensitivity of electrons to thermal disturbance of quantum states and because of the much higher RF loss compared to optical loss for these low signal levels. Since the signal levels are so low, the extreme sensitivity offered by the high EO coefficient of chromophores is important. And because the pulses are so fast, the high bandwidth of EOP based transducers is important.

Planck's possible perspective

As GenAI changes our lives and we look to quantum computing to solve previously intractable problems, it is healthy to look back. From Planck's perspective, we have unimagined possibilities before us. One example we discussed is the potential of electro-optic polymers as an enabler of quantum computing. Our hope is that quantum computing in general will enrich the quality of life for all of us.

Michael Lebby is chief executive officer and **John Zyskind** is vice president of engineering, both at Lightwave Logic, Englewood, CO; e-mail: info@lightwavelogic.com; www.lightwavelogic.com.