LASER FOCUS WORLD®

# Taking Innovation to the Next Level

Photonics is now one of the fastest growing market segments, with a regular pattern of patented innovations fueling steady growth year over year. The continued success of the photonics community has been the direct result of constant innovation. Continuously finding new ways to tap into the power of light to address a growing array of applications stretching across industry boundaries is taking innovation to the next level.

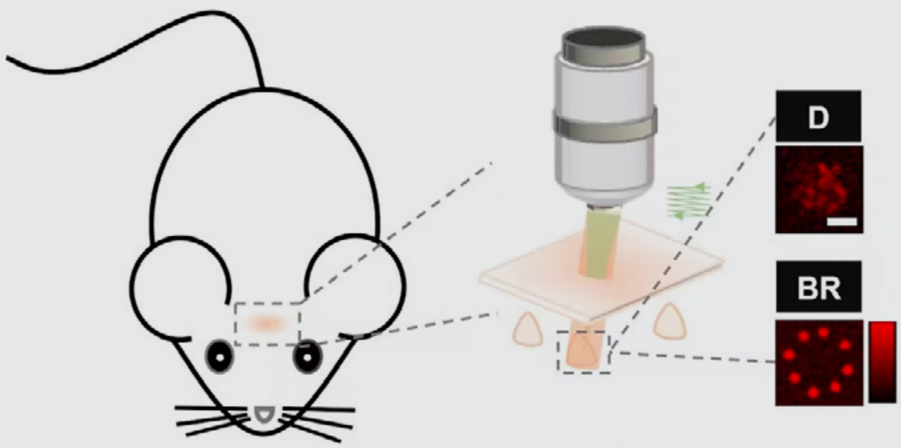
Of course, such innovation does not just happen. It understandably takes the dedication of researchers, engineers, and scientists willing to continuously push the envelope and find new ways to utilize photonics. Understandably, achieving the type of accurate and repeatable results for diverse solutions requires the right mix of precision equipment capable of enabling such innovations to extend from the lab to real-world applications. For example, with a tunable range of a wide frequency and phase control enabling synchronization to external references, the Stanford Research Systems' SR542 Precision Optical Chopper provides photonics professionals with ultra-stable and flexible optical chopping.

This report takes a closer look at some prime examples of innovations within photonics. Highlights include innovations such as optogenetic advances, developments within quantum gravity gradient sensing, photon detection enabling quantum communications, and hyperspectral digital holography. None of these advances would be possible without only providing forward-looking professionals with the right equipment.

# QUICK TWO-PHOTON OPTOGENETICS FIX ENABLES ALL-OPTICAL PHYSIOLOGY

Researchers in China outmaneuver current two-photon optogenetics shortcomings by simply changing the phase patterns displayed within any existing computer-generated holography-based two-photon optogenetics systems.

**BY SALLY COLE JOHNSON, ORIGINALLY PUBLISHED MAY 31, 2022**




*Schematic diagram of the all-optical physiology system. Green: the beam for two-photon calcium imaging. Red: the beam for two-photon optogenetics. Diagram at right: excitation pattern distributions tested with 1-micron fluorescent beads. D: disk pattern. BR: beaded ring pattern. Scale bar: 5 microns.*

To map the functional connectivity of neural circuits *in vivo* (inside a living animal), two-photon optogenetics is indispensable because it allows neuroscientists to noninvasively manipulate neural activities at high spatial resolution. It does come with a few challenges, but researchers at Tsinghua University in China discovered a quick fix to enable all-optical physiology.

"Considering that functional imaging of neural network activity only provides correlations of neural connectivity, the combination of functional imaging and optogenetics, called 'all-optical physiology,' is attracting great interest for its potential to reveal the causality of functional connectivity," says Lingjie Kong, an associate professor in the Department of Precision Instruments, who recently presented his group's work at the 2022 Biophotonics Congress.

Kong's group is devoted to developing novel tools to enable neuroscience studies, and in 2018 he was honored by MIT Technology Review as one of the "35 Innovators Under 35" in China for his work with neuroimaging that enables real-time observation of neural activity across different brain regions within conscious animals.

"We've developed a high-speed volumetric imaging system based on an ultrasonic lens, a deep tissue imaging system based on multi-pupil adaptive optics, and a centimeter-scale micrometer-resolution macroscope of gigapixel throughput," Kong says. "And we realized the urgent need for all-optical physiology, which currently lacks efficient and precise manipulation techniques."

### TWO-PHOTON OPTOGENETICS AND COMPUTER-GENERATED HOLOGRAPHY

To ensure selective simulations of neurons, "two-photon optogenetics is desirable, because effective simulations only occur around the laser focus, where the photon intensity is high enough," explains Kong. "In practice, two-photon optogenetics based on computer-generated holography (CGH) is generally used because it enables multi-foci generation to stimulate targeted neural ensembles simultaneously."

But, as Kong points out, opsins (akin to tiny solar cells) are on cell membranes. To ensure efficient stimulation, enough opsins need to be activated to generate action potentials.

"In fact, the size of neurons within a mouse cortex ranges from 10 to 20 μm, much beyond the laser focus size of conventional two-photon systems," he says. "In earlier efforts, extended laser foci, such as disk patterns, were designed to match the size of neurons. No doubt extended stimulation patterns are generally of low axial resolutions, which would lead to mis-stimulation. Moreover, the speckles in extended patterns decrease stimulation efficiency."

### OPTICS INVOLVED

Two-photon optogenetics achieves excitation or inhibition of neural activity in neuroscience based on a nonlinear optical process, two-photon excitation (2PE). "Compared to one-photon excitation-based optogenetics, two-photon optogenetics can achieve precise stimulation within deep tissues, thanks to the inherent optical-sectioning capability of 2PE and the increased robustness to scattering of the longer-operation wavelengths," points out Kong.

CGH is a technique to obtain a complex optical field via numerical calculation. "For two-photon optogenetics based on CGH, you calculate a hologram pattern based on spatial distributions of targeted neural ensembles, via computer, then display the hologram pattern onto a spatial light modulator for selective stimulation," he says.

And all-optical physiology is an integrated optical technique for stimulating and recording neuron activities simultaneously. "In our proposed system, two-photon fluorescence imaging and two-photon optogenetics are integrated, which enables deep tissue imaging and stimulation of neural activities in vivo, at high spatio-temporal resolutions," Kong adds.

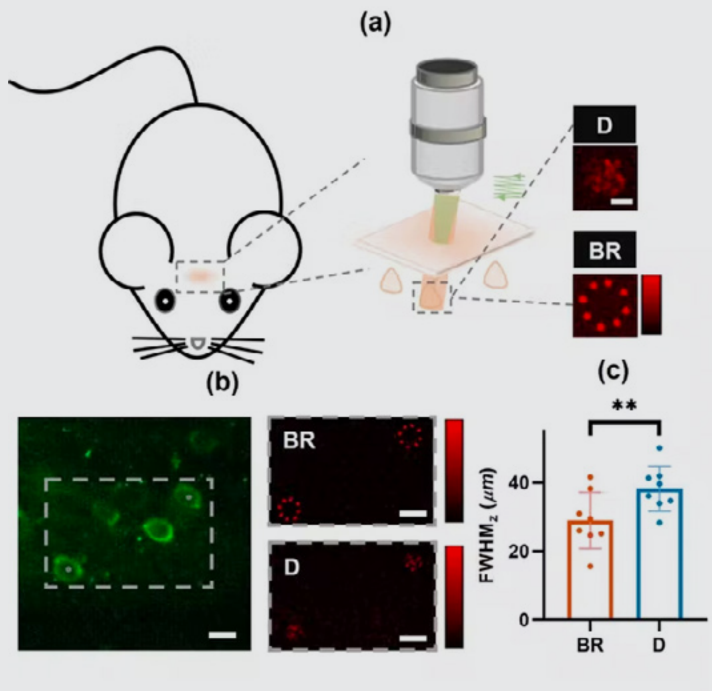
Commonly used extended stimulation patterns for two-photon optogenetics fail to achieve single-neuron resolution—particularly within the axial dimension, where inherent speckles decrease stimulation efficiency.

### A QUICK FIX

Instead of using complex techniques to improve axial resolution or eliminate speckles, "we propose using speckle-free beaded-ring patterns for two-photon optogenetics," says Kong. "It achieves both high axial resolution and high stimulation efficiency. We demonstrated its superior advantages via two-photon optogenetics based on all-optical physiology within a mouse's primary somatosensory cortex *in vivo*." (See figure.)

The most surprising aspect of this work was the discovery of an inexpensive alternative way to get around shortcomings in current two-photon optogenetics by simply changing the phase patterns displayed within any existing CGH-based two-photon optogenetics systems—without making any other changes. "It's a good substitute for existing technologies," Kong says.

With advanced techniques available now, Kong and colleagues are working toward all-optical physiology for simultaneously optical recording and manipulating neural activities across cortical layers or areas in vivo. "Our method will enable the study of long-range functional connectivity for the first time," he adds.




*All-optical physiology test with different stimulation patterns on multiple neurons in vivo. a) Schematic diagram of the all-optical physiology system. Green: the beam for two-photon calcium imaging. Red: the beam for two-photon optogenetics. Diagram at right: excitation pattern distributions tested with 1-micron fluorescent beads. D: disk pattern. BR: beaded ring pattern. Scale bar: 5 µm. b) Left: a typical two-photon image of neurons in L2/3 of mouse S1 cortex. Locations of gray spots are the center of two excitation patterns. Right: the intensity distribution of excitation patterns to stimulate target neurons. Scale bar: 10 µm. c) mean axial resolutions of calcium signals of multiple neurons under different simulation schemes. **p=0.0086, ratio paired t test. Compared with disk patterns, the average axial resolution of neurons in a group stimulated by beaded-ring patterns is increased by 24.27%.*

# QUANTUM GRAVITY GRADIENT SENSOR DETECTS OUTDOOR TUNNEL

**Existing measurement technologies are susceptible to vibrational noise, but a practical quantum gravity gradient sensor overcomes this issue and may revolutionize our understanding of the subsurface world.**

**BY JAMIE VOVROSH, ORIGINALLY PUBLISHED APRIL 20, 2022**


*FIGURE 1. The quantum technology-based gravity gradient sensor.*

By measuring small variations in the Earth's gravitational field, it is possible to gain useful information about what lies underground. This can be used for a range of applications including mineral and resource exploration, aquifers, geological mapping, civil engineering, and archaeology. When used for these applications, the advantage of gravity sensing is the intervening media does not attenuate gravity—the range of what can be detected is limited by the sensitivity of the sensor used and not the ground conditions. Despite the advantages of gravity measurements, gravity sensors are used infrequently due to commercial considerations.

Existing gravity sensors are sensitive to vibration, tilt, and drift over time, which can severely limit the speed and usefulness of surveys. This is due to the need to integrate ground vibrations, which are often 10–100X larger than the signal of interest, align the instrument to better than 1/1000th of a degree, and perform repeated measurements on the same point during the course of a survey to remove drift. These limitations mean existing spring-based gravimeters are slow compared to other geophysical sensors.

Gravity sensing is typically only used for jobs where other geophysical sensors would fail to deliver the information required. For example, when ground penetrating radar is not effective because of ground conditions.

Cold atom- and quantum technology-based gravity sensors have shown unprecedented performance in labs around the world, and their inherent low drift1 offers a route to solving the limitations currently present in existing gravity sensors. Here, we discuss the first demonstration of a quantum technology-based gravity gradient sensor to detect a subsurface feature in an outdoor environment.[2]

## GRAVITY GRADIENT SENSOR

The University of Birmingham, as part of the UK's Quantum Technology Hub for Sensors and Metrology, developed a new gravity gradient sensor to overcome the aforementioned challenges (see Fig. 1).

The sensor operates by creating two clouds of ultracold rubidium atoms held in separate magneto-optical traps in an hourglass configuration. The clouds are positioned so one is 1 m above the other. Each cloud is then cooled to millikelvin temperatures before being released simultaneously, at which point the clouds undergo freefall inside the vacuum chamber. During freefall, a sequence of counterpropagating laser pulses is fired at the clouds to create two atom interferometers that can each measure the local acceleration due to gravity. The difference in local gravity between the two clouds is extracted from the experiment.

As part of this subtraction, common noise to both atom interferometers such as vibration is removed. In addition to the common mode suppression of noise sources, this subtraction means misalignments from the vertical are correlated for the pair of clouds, giving a reduced susceptibility to tilt misalignment.

The laser system is a critical subsystem within the sensor and must provide stable high-power, narrow linewidth light via a series of pulses. Each of these pulses need to be precisely timed and delivered with particular polarizations, powers, and frequencies, all while being robust to instrument movement and environmental conditions.

To achieve this, the current iteration of the laser system is mainly composed of fiber-connected frequency-doubled telecom technology, which allows for a robust and transportable instrument. The optical power from the seed laser is amplified by erbium-doped amplifier modules; the light is switched on and off with acousto-optic modulators. The frequency of the laser is controlled by electro-optic modulators, and prior to its use on the atoms the wavelength is converted from 1560 nm to 780 nm by second harmonic generation using periodically poled lithium niobate crystals.

The sensitivity and stability of the instrument was evaluated in static operation outdoors at a measurement rate of 0.7 Hz and found to have a statistical uncertainty of 20 E within 10 min of measurement time. This is equivalent to a 1.4 ng uncertainty for each of its two gravimeters and surpasses the reported performance of commercial gravimeters for survey applications by a factor of 1.5–4.[3]

## FEATURE DETECTION

As part of the Innovate UK-funded Gravity Pioneer project to demonstrate the sensor's potential for gravity cartography, it was trialed outdoors over a buried feature. To test the sensor, a 0.5 m spatial resolution survey was performed along an 8.5 m survey line above a pre-existing multi-utility tunnel under a road on the University of Birmingham's campus (see Fig. 2). The tunnel itself had a 2 × 2 m internal cross-section and a reinforced concrete wall of approximately 0.2-m thickness. The sensor detected the tunnel with a signal-to-noise ratio of 8, and through the use of inference on the data, the horizontal position of the tunnel center was deduced to (0.19 ± 0.19) m along the survey line and a depth to the center of (1.89−0.59/+2.3) m.

This result is the first demonstration of submeter-resolution mapping with a quantum gravity sensor. The repeatability of the prototype during the survey was similar to that of commercial gravimeters and was limited by systematic effects. Its accuracy locating the tunnel would also be extremely useful for a range of applications, including civil engineering.

## FUTURE OUTLOOK

The reduced drift, reduced susceptibility to tilt misalignment, and removal of vibration noise enables this sensor to overcome the limiting factors of existing gravity measurements, opening up not only faster measurement times, but opportunities to use gravity sensing in environments where vibrational noise would have either resulted in a high level of complication or made existing gravity sensors unusable.

While the performance of the sensor demonstrated here is suitable for many geophysical applications, the full potential of quantum gravity gradient sensors has not yet been reached. Through implementation of further scientific enhancements to the sensor and engineering improvements, there is potential to provide a further 10- to 100-fold

*FIGURE 2. Inside the service tunnel detected with the quantum sensor.*

improvement in instrument sensitivity, allowing faster mapping or detection of smaller and deeper features. It is expected such performance will be achieved in practical instruments within the next 5–10 years.

When quantum gravity gradient sensors become widely commercially available, it will be possible to map out the world beneath our feet in unprecedented detail. These sensors could be used in a diverse array of applications, including performing noninvasive surveys of archaeological sites, charting complex cave systems, measuring the time-varying flow of groundwater, and reducing the risks of unforeseen ground conditions ahead of construction and infrastructure projects.


## ACKNOWLEDGEMENTS

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# THE EVOLUTION OF SINGLE-PHOTON DETECTION

A century of scientific advances is enabling some of the future's most exciting technologies, including those enabling quantum communications and other applications that are continuing to emerge.

**BY RICHARD SIMONS, ORIGINALLY PUBLISHED DECEMBER 17, 2021**

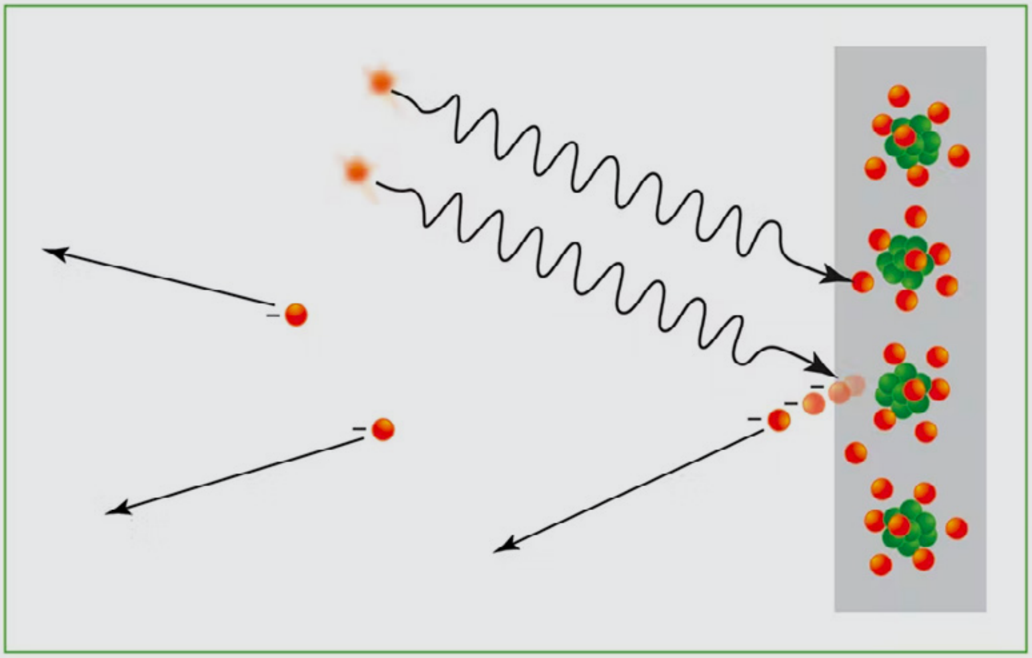

*FIGURE 1. The photoelectric effect in a solid.*

Single-photon detection has become a vital tool in many applications, from single-molecule fluorescence, particle characterization through scattering, and quantum cryptography to astronomy, lidar, and more. The concept appears to be simple in principle—one photon creates one electron in a photodiode or when hitting a metal surface—but how easy is it to detect that single electron?

Development of single-photon counting stems from discovery of the photoelectric effect in the late 19th century. Later, it was achieved in silicon avalanche photodiodes (APDs) in the 1960s. Today, turnkey modules provide simple, plug-and-run photon detection in OEM instruments and research laboratories alike. Single-photon detection is now enabling quantum communications, as it's being deployed in space and underground in fiber networks, and in new single-molecule and small-particle characterization applications, with future development and uses continuing to emerge.

## EARLY SCIENTIFIC DISCOVERIES

Late in the 19th century, Heinrich Hertz's 1887 observations sparked experiments investigating the effect of light, particularly UV radiation, on charged bodies. Scientists then discovered that while the number of particles (electrons) emitted from a surface was proportional to light intensity, the electron's maximum kinetic energy was proportional to radiation frequency, and that no electrons are emitted below a minimum frequency (see Fig. 1).

This work, coupled with Max Planck's studies on blackbody radiation, led to Einstein's Nobel Prize-winning paper proposing that light energy is carried in discrete packets (photons); the energy within each packet equals the light frequency multiplied by a constant (explaining the photoelectric effect); and only photons with high-enough frequency have enough energy to liberate an electron from a particular material. Since a photon can release an electron from a metal surface, a single photon can be detected by finding the negatively charged electron. Although simple in concept and relatively easy to do when large numbers of photons liberate large numbers of electrons, detecting one single electron is complicated.

## TECHNOLOGY DEVELOPMENT

In 1902, Austin and Starke discovered that metal surfaces impacted by electron beams in a cathode-ray tube emitted more electrons than were incident onto the surface, leading to application of secondary emission to amplify signals. In 1934, RCA created the first photomultiplier tube (PMT) by combining a photocathode (creating electrons through the photoelectric effect) and a secondary emission stage in the same vacuum tube (see Fig. 2).

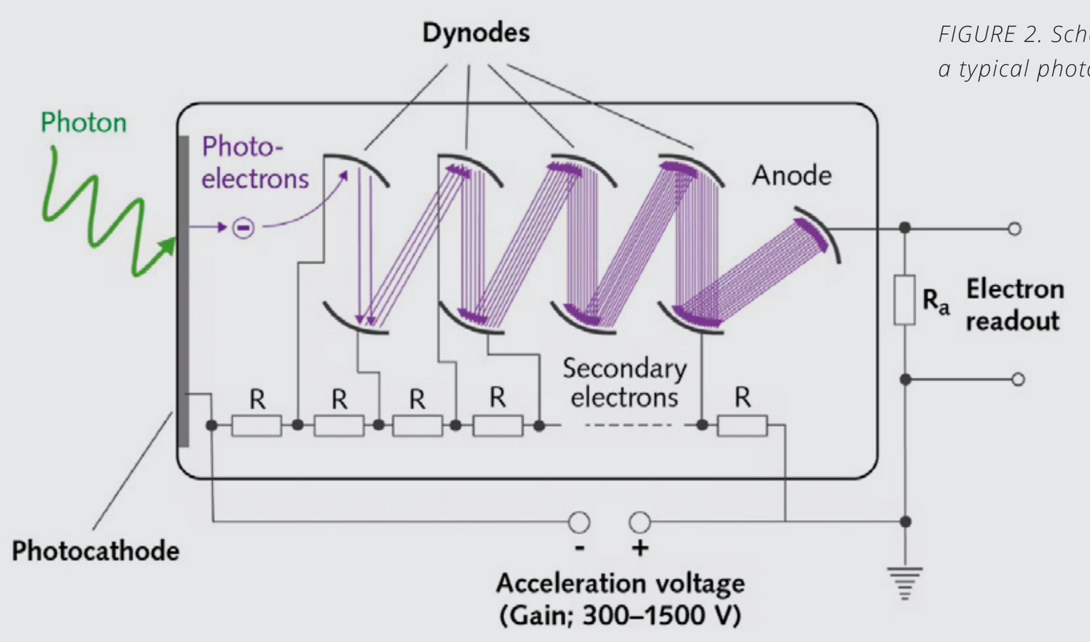


*FIGURE 2. Schematic of a typical photomultiplier.*

With an approximate gain of 8, the PMT enabled the single photon to liberate eight electrons to prove its presence. With further improvements in photocathodes and multiple amplification stages, a typical gain of $10^6$ is now possible in linear mode.

However, for single-photon detection, voltages across multiplication stages can be increased to raise the gain so high that a single photoelectron from the photocathode produces a very large current at the output circuit. This process tends to be self-sustaining, so control electronics are needed to detect the current and reset the PMT, leading to dead time where no electrons can be multiplied and therefore no photons detected. This method of operation, similar in principle to that of a Geiger counter, is known as Geiger mode.

Since the photocathode is far from 100% efficient, not every photon will generate an electron. Different photocathode materials respond to different wavelength ranges and have different photon energies below which they will not emit electrons. Electrons can also be emitted by other means (e.g., thermionic emission, where thermal energy boosts the electron enough to escape the electrode), giving rise to "dark electrons," which, when operated in Geiger mode, leads to "dark counts" with no photons present.

Because the PMT can detect low levels of light, even down to the single photon, it has become an important tool in many applications including astronomy, nuclear particle physics, and biomedical instrumentation. However, PMTs are very sensitive to overstimulation and are easily damaged by exposure to ambient light. They operate typically at a 1–2000 V difference between the anode and cathode, with the anode at low voltage to allow for easier measurement of the photocurrent by low-voltage circuitry—so the cathode is at a large negative voltage. The PMT is also susceptible to magnetic fields, which can cause electron paths to curve and miss their targets, reducing gain; therefore, magnetic shielding is needed often at the cathode potential, creating a need for additional electrical insulation.

When Bell Laboratories invented the p-n junction in 1939, another route to single-photon detection—the photodiode—emerged. The *p-n* junction is the interface between differently doped regions within a single crystal of semiconductor. The *p* (positive side of the junction) lacks electrons where they would be expected within the crystal lattice; the missing electrons are termed "holes." The *n* (negative) has an excess of electrons in the outer shells of the otherwise neutral atoms in the crystal lattice. This creates a diode, allowing passage of electrical current in only one direction under normal operation. A photodiode in its simplest form is a *p-n* junction whose materials enable the right radiation frequency or wavelength to release electrons and create a photocurrent within the junction. When reverse-biased with the cathode voltage raised positive compared to the anode, this photocurrent can be quickly extracted to produce a current proportional to the light level on the photodiode.

Adding an undoped region ("intrinsic" semiconductor) between the *p*- and *n*-type regions allows doping levels to be increased, causing higher levels of charge carriers and therefore greater operation speed. A PIN junction, invented by Jun-ichi Nishizawa et al. in 1950, is also ideal for a photodiode. Routine applications using PIN photodiodes range from fiber-optic communications to medical instrumentation and laser warning systems. But they are still limited to one photon creating one electron.

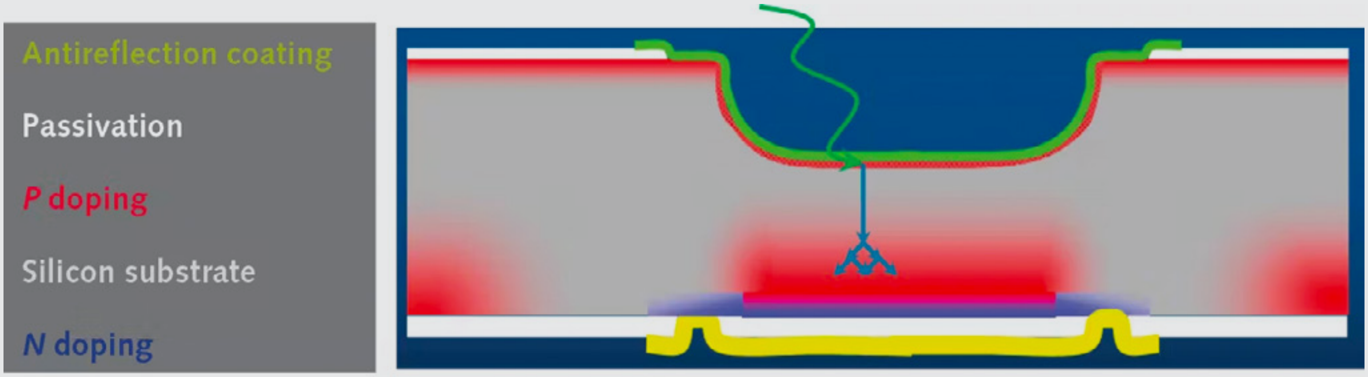


*FIGURE 3. A typical avalanche photodiode (APD) structure.*

## AVALANCHE PHOTODIODES

Adding an internal current gain region within a PIN photodiode turns it into an APD (see Fig. 3). Invented by Nishizawa in 1952, the APD uses a careful doping structure to allow high-voltage application, creating high fields within the junction region.

These high fields accelerate the photoelectrons, causing them to release other electrons through impact ionization and create a typical internal current gain of 100. Thus, a single photon can create 100 photoelectrons—however, this is still not enough to enable a simple single-photon detector.

In the 1960s, Robert McIntyre at RCA Canada (part of the same organization that developed the PMT, where Excelitas now makes its single-photon counting modules [SPCMs]) researched microplasma instability in silicon. This, in turn, led him to research APD behavior in Geiger mode, where the high reverse-bias causes the APD's dark current to spontaneously create a self-sustaining avalanche. With an APD in Geiger mode, a single photon can produce enough current to be detectable. However, once a single photon has created the avalanche and a current is generated, the APD becomes useless without a method to control it. After the single photon has been detected, nothing else ever will be; this is not particularly useful.

## GETTING CLOSER

RCA's work led to two key developments in the search for a working single-photon detector. First, improvements in silicon crystal growth led to the 1986 super-low ionization coefficient (k-factor) APD, or SLiK (see Fig. 4). Since it has no photo- and negligible dark-electron stimulus, the SLiK APD can be biased to above breakdown without

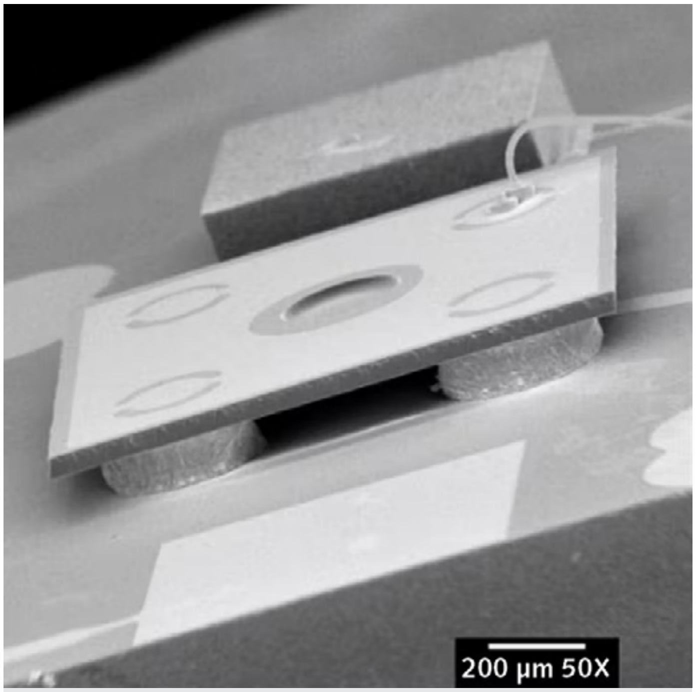


*FIGURE 4. The SLiK APD, optimized for single-photon detection.*

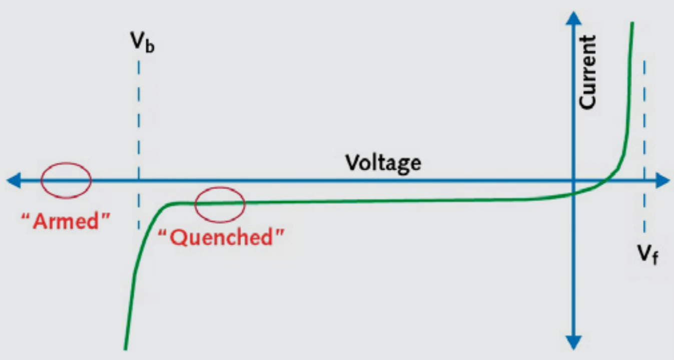


*FIGURE 5. Current vs. voltage diagram of an APD, showing "armed" and "quenched" states.*

immediately initiating an avalanche.

Cooling the APD can significantly reduce the thermionic emission of electrons, increasing the time available to detect an incoming photon.

To stop the avalanche, and allow the detection of another photon, an in-line resistor to the bias circuitry is added, creating a passive quench circuit (see Fig. 5). When the current starts flowing, some of the bias voltage is dropped across the resistor, leaving less voltage across the APD until it becomes so low that statistical variations in the photocurrent cause it to drop to zero and it cannot self-start. This causes the voltage across the resistor to return to zero, leaving the full voltage across the APD, which is now ready to detect another photon.

Launched by RCA in 1987, the SPCM-100 was a self-contained, user-friendly device with built-in temperature control, stabilized high-voltage supply, and a Geiger-mode APD passive-quenching circuit. An on-board logic circuit detected the avalanche current pulse and generated a simple TTL pulse of 35 ns, and the passive quench circuit readied the APD for the next photon after only 60 ns. With its low dark-count, low timing jitter, low after-pulse, and a photon-detection efficiency (PDE) of over 50%, this first-generation module enabled single-photon studies to move deeper into red and near-infrared regions of the electromagnetic spectrum that were difficult to reach with PMTs. APDs' much lower bias voltages, and their immunity to magnetic fields, eliminates the need for complex shielding, and APDs are also less vulnerable to accidental ambient light exposure. This development made single-photon detection readily achievable, becoming a useful tool to enable new discoveries and applications.

In 1990, RCA Canada became EG&G, and SPCM development continued. Passive quenching was replaced by a patented active-quench circuit, using the logic that detected the avalanche current to actively control the bias across the APD, rather than relying on voltage build-up across a resistor. Pulse width and dead time were reduced, and better control of bias voltage and silicon purity enabled increased PDE to >65% and decreased dark-count rates to 25 counts per second.

EG&G acquired the Analytical Instrumentation Division of PerkinElmer in 1999, upgraded the SPCM with a pulse width of 20 ns and dead time of 35 ns, and established its RoHS compliance. In 2010, the optoelectronics division of PerkinElmer was spun out to create Excelitas Technologies. In 2011, improved control electronics allowed PDEs as high as 70% while retaining industry-leading specifications for dark count and after-pulsing. The pulse width and dead time were both further reduced, affording 10 ns and 24 ns, respectively, to reliably detect over 37 million single-photon events per second.

## EXPANDING APPLICATIONS

The market and applications for single-photon detection continue to expand. Different APD technologies for detecting single photons optimize key performance parameters to suit different applications. For automotive lidar at 905 nm, where cost is important for volume production, single-photon silicon avalanche detectors use micro-APDs on top of a CMOS structure. New indium gallium arsenide (InGaAs) Geiger-mode APDs can detect single photons at 1.5 µm, with higher-power lasers allowing significantly greater range to detect photons that are reflected back by objects around the vehicle.

InGaAs APDs for single-photon detection will also play a vital role in infrastructure and banking security as quantum key distribution (QKD) systems are deployed on fiber-optic links at telecom wavelengths. QKD allows two parties to set up a secure cryptographic key remotely in real time, without needing physical contact to share the key. QKD has already been demonstrated in free-space links on the ground and in satellite-ground and satellite-satellite links, using both silicon and InGaAs APDs.

As bandwidths increase, not only is photon detection important, but jitter in the time delay from the photon reaching the surface of the APD and the system output pulse being registered also becomes a key performance parameter. QKD relies on comparing a sequence of photons arriving at various detectors—if the internal delay time varies too much, it will be impossible to know which photons are being compared. APDs with small surface areas and thin structures can create the avalanche with much less variability in time delay, so their reduced detection performance compared to larger APDs is tolerated for applications where timing resolution is important.

Many applications leveraging the quantum nature of single atoms or electrons also need to be able to detect single photons. A single electron trapped in a crystal defect can only emit one photon at a time, so a single-photon detector is needed to understand this electron's interactions. Creating an entangled photon pair starts with a single photon—again, the single-photon detector is a vital tool for characterization and monitoring of single-photon sources.

With development of ever-smaller features on electronic wafers, air and water cleanliness in semiconductor wafer fabs becomes more critical to their operation. Single-photon counters with high detection efficiency and low dark-counts are often key parts of monitoring systems in ultra-clean workspaces. High detection efficiency minimizes estimations for translating detector response to contamination levels, which reduces the likelihood of missing small increases in contamination levels. On the other hand, a low, stable dark count reduces false counts that may lead to false alarms and cause unnecessary and expensive shutdowns.

Recently, detection of small particles and single molecules has become an important application for single-photon detection. This technique provides ultimate sensitivity for environmental monitoring or diagnostic measurements.

SPCMs continue to support applications including astronomy, flow cytometry, fluorescence lifetime, particle sizing, and wind lidar, as well as recent and developing applications including but not limited to quantum computing, QKD, and single-molecule analysis.

# HOLOGRAPHY GOES HYPERSPECTRAL

**A new technique, hyperspectral digital holography, is advancing and enriching conventional holography with optical frequency combs.**

**BY NATHALIE PICQUÉ, JUSTINE MURPHY, ORIGINALLY PUBLISHED JANUARY 24, 2022**

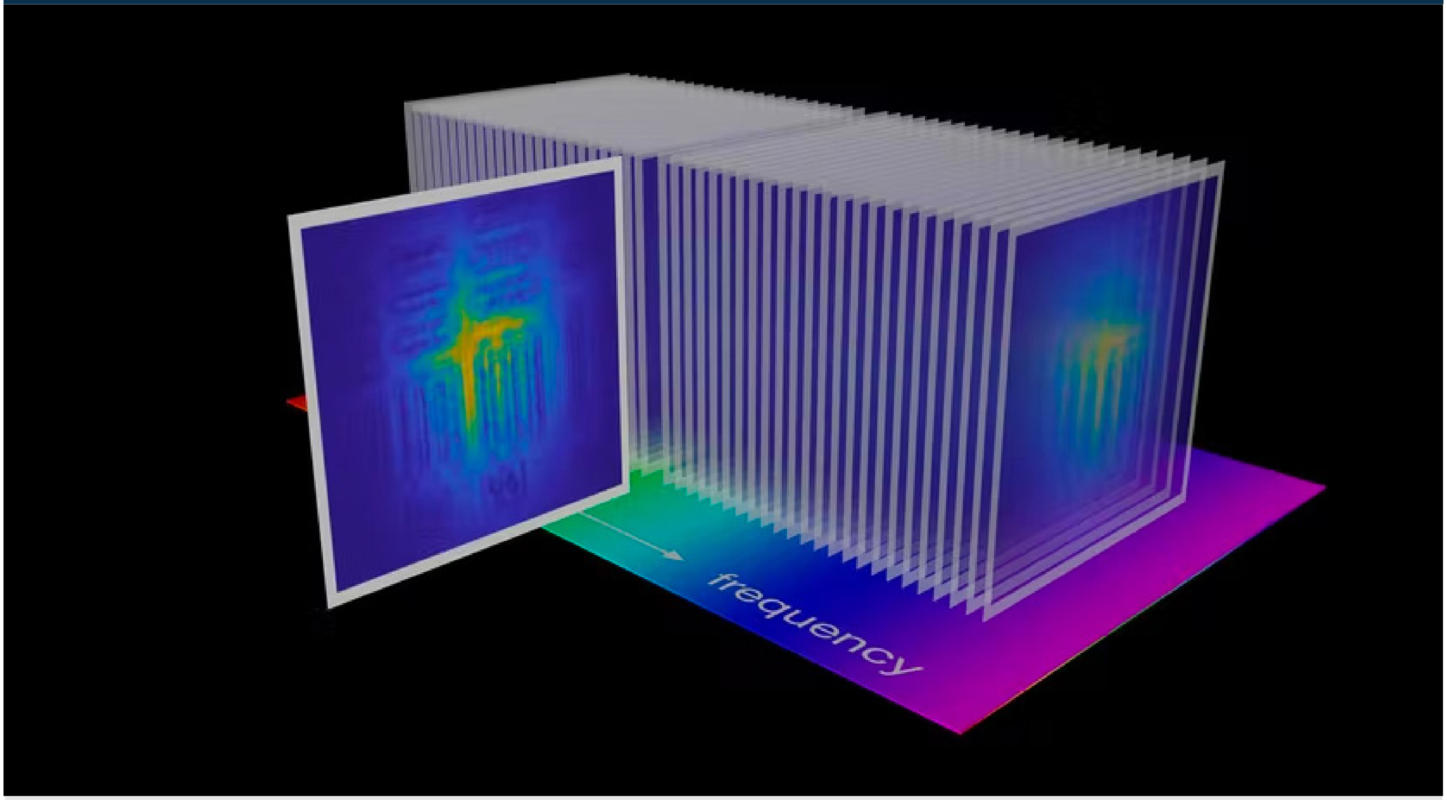


*FIGURE 1. In dual-comb digital holography, as many holograms as there are comb lines are created.*

Holography and holograms have long been used in documents such as bank notes and passports, and even demonstrated in movies—*Star Wars* is a great example. But while this method for 3D imaging and displays (among other applications) remains powerful, there is room for improvement.

A new technique—hyperspectral digital holography, developed by a team at the Max Planck Institute of Quantum Optics (MPQ; Garching, Germany)—is advancing and enriching conventional holography with optical frequency combs. Their work presents a combination of features that were presently unavailable for holography.

*Laser Focus World* spoke with Dr. Nathalie Picqué, a scientist at MPQ whose group led the study, about this new technique and the novel advances it is prompting.

**LASER FOCUS WORLD: WHAT WAS INVOLVED WITH YOUR RESEARCH IN DEVELOPING THIS NEW TECHNIQUE?**

**Dr. Nathalie Picqué:** Our group at the Max Planck Institute of Quantum Optics has been exploring new approaches to interferometry with frequency combs for more than 15 years. A frequency comb is a spectrum made of evenly spaced phase coherent laser lines. We have been very involved in developing dual-comb interferometry, where one records the time-domain interference between two frequency combs of slightly different repetition frequencies. Dual-comb interferometry has been mostly exploited in the form of dual-comb spectroscopy, a technique of Fourier transform spectroscopy (also known as FTIR) without moving parts.

Spectra can be measured over a broad spectral bandwidth with high accuracy and resolution and short measurement times. In dual-comb spectroscopy, the interference is detected on a single photodetector. With the idea of extending the technique toward hyperspectral imaging, where the single photodetector is replaced by a camera sensor, one gets as many spectra as there are detector pixels and this is powerful for spectroscopically characterizing samples which are spatially inhomogeneous.

Once we had the setup operating for hyperspectral imaging, I realized that we might get much more from the same setup, because the layout was reminiscent of digital holography. So, we just tried to implement holography with our frequency combs and it worked very well. Then, we combined the holography with the hyperspectral gas sensing and it worked just as well.

**LFW: HOW DOES THIS NEW IMAGING TECHNIQUE DIFFER FROM EXISTING HOLOGRAPHY METHODS?**

**Picqué:** We simultaneously record many holograms (one per comb line). We experimentally demonstrate 100, but it can potentially be several tens of thousands. This is done with a set-up which is not bigger than a traditional digital holography setup and there are ideas to miniaturize this further. Usually in digital holography, a monochromatic laser source (sometime two or three) is used, so that one gets one hologram at a time.

Getting more into details, our technique presents a combination of features that were presently unavailable for holography: use of light sources of broad spectral span but of long temporal coherence, recording technique where all the signal is simultaneously measured.

**LFW: WHAT DOES THIS NEW TECHNIQUE ACCOMPLISH THAT EXISTING METHODS CANNOT?**

**Picqué:** There are several advantages in recording many holograms simultaneously.

One is that with a single hologram at a single color (optical frequency), only the last digits of the distance measurements are known—for instance, you cannot say if your distance is 0.00000010 meters or 15.00000010 meters—whereas with many frequencies, you can lift this ambiguity. As the spacing between the comb lines is usually on the order of 100 MHz, the technique is even suitable for fairly large objects (100 MHz corresponds to ambiguity ranges of 3 meters).

Of course, one can use a tunable laser and measure different frequencies at different times in a sequential manner (and this has been demonstrated by others in the past), but one may add errors if the scene changes during the sequence. Measuring all frequencies at once is going to improve the precision of the measurements. It makes it possible also to add time resolution: if the scene changes over a time scale slower than the measurement time, one could measure dynamic scenes that show a time evolution.

Also, using simultaneously many frequencies means that several optical diagnostics can be simultaneously performed. In our [study], we show that one can combine holography with hyperspectral gas sensing, with a single setup and a single measurement. This is a 4D diagnostic (3D spatial and 1D spectral).

Finally, the laser sources that we use are frequency comb generators. Not only are many narrow laser lines simultaneously emitted, but the absolute frequency of each of these lines can be known within the accuracy of an atomic clock. Perhaps this will enable it to enhance the accuracy of holography.

In summary, we hope to bring to holography new potentialities by improving its capabilities for frequency multiplexing, its accuracy, its precision, its speed, and its ambiguity range.

### LFW: WHAT CHALLENGES DOES THIS NEW TECHNIQUE OVERCOME?

**Picqué:** By enabling the simultaneous measurements of many holograms, which was previously not possible, the new technique opens up some intriguing prospects for metrology of 3D objects and for performing several complementary optical diagnostics with a single apparatus.

### LFW: FOR WHAT APPLICATIONS IS THIS TECHNIQUE BEST SUITED?

**Picqué:** Precise wavefront sensing and three-dimensional metrology (optical contouring and deformation measurements, 3D profiling) are obvious applications. This is, for instance, very important for characterizing precisely machined objects, such as optical components especially for the UV, or nanofabricated objects from lithography.

Holography is also widely used in microscopy, in particular for life science applications. We are wondering if frequency combs could bring something to this field and this is something we are willing to explore.

### LFW: WHAT DO YOU ANTICIPATE FOR THE FUTURE OF THIS TECHNOLOGY AND METHOD?

**Picqué:** We have performed a successful proof-of-principle demonstration of a new concept. We are currently developing a dedicated system, with a fast camera, and we are exploring more quantitatively the limits of our technique. We hope to further improve our technology.

In the near future, we should see a dramatic increase in the number of comb lines, of the span, and a significant improvement of the measurement speed and the spatial resolution. The success of the new technology will strongly depend on how far we will be able to push the technique. We hope to bring new tools for precise 3D phase imaging that will have a significant impact in various fields of science and technology. If the technique is really worth it, it will open up applications that we cannot foresee today.

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