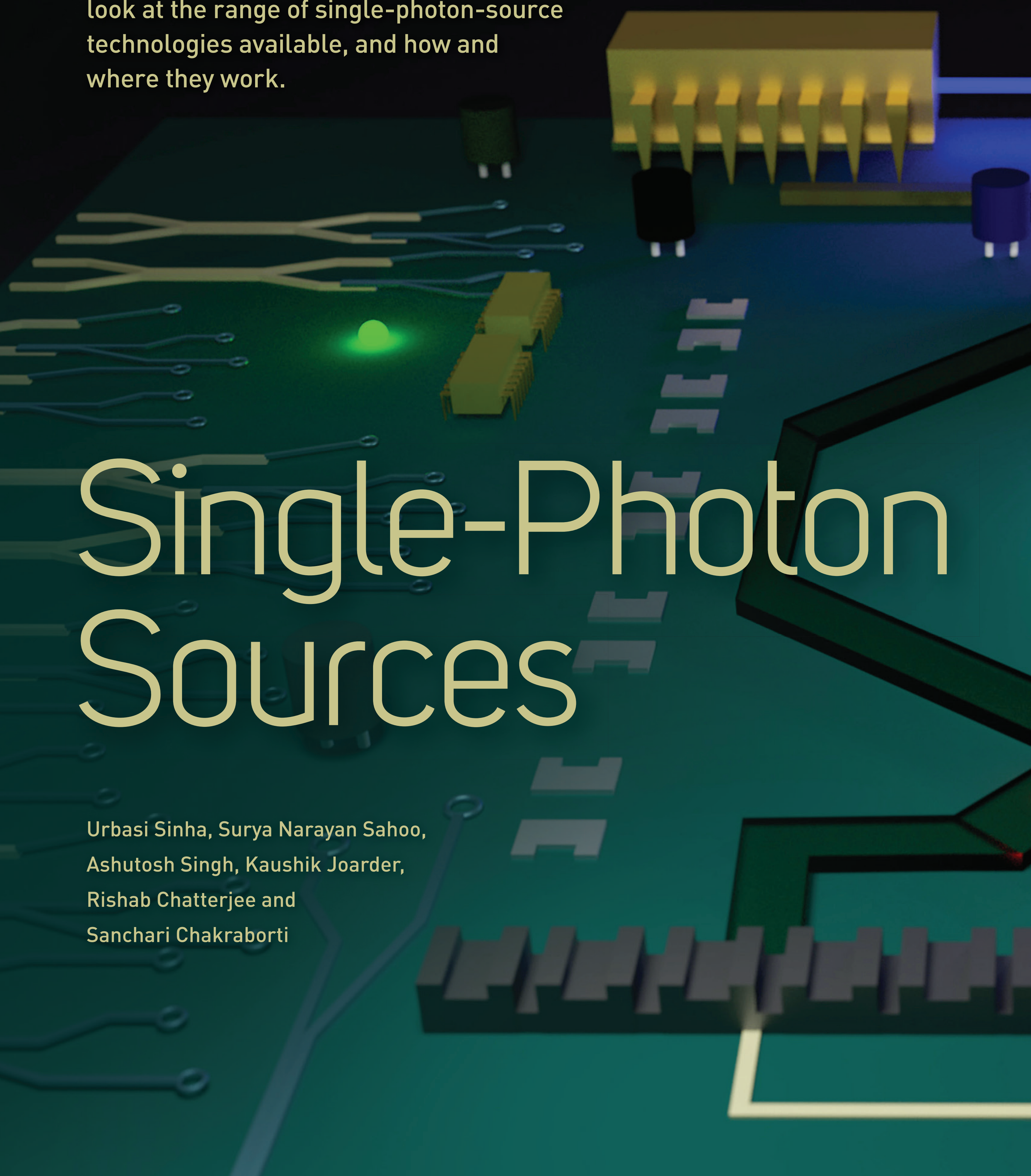
Exploring and extending the promise of quantum technologies requires the ability to work with single quantum objects—especially photons. Here's a look at the range of single-photon-source technologies available, and how and where they work.



Single-Photon Sources

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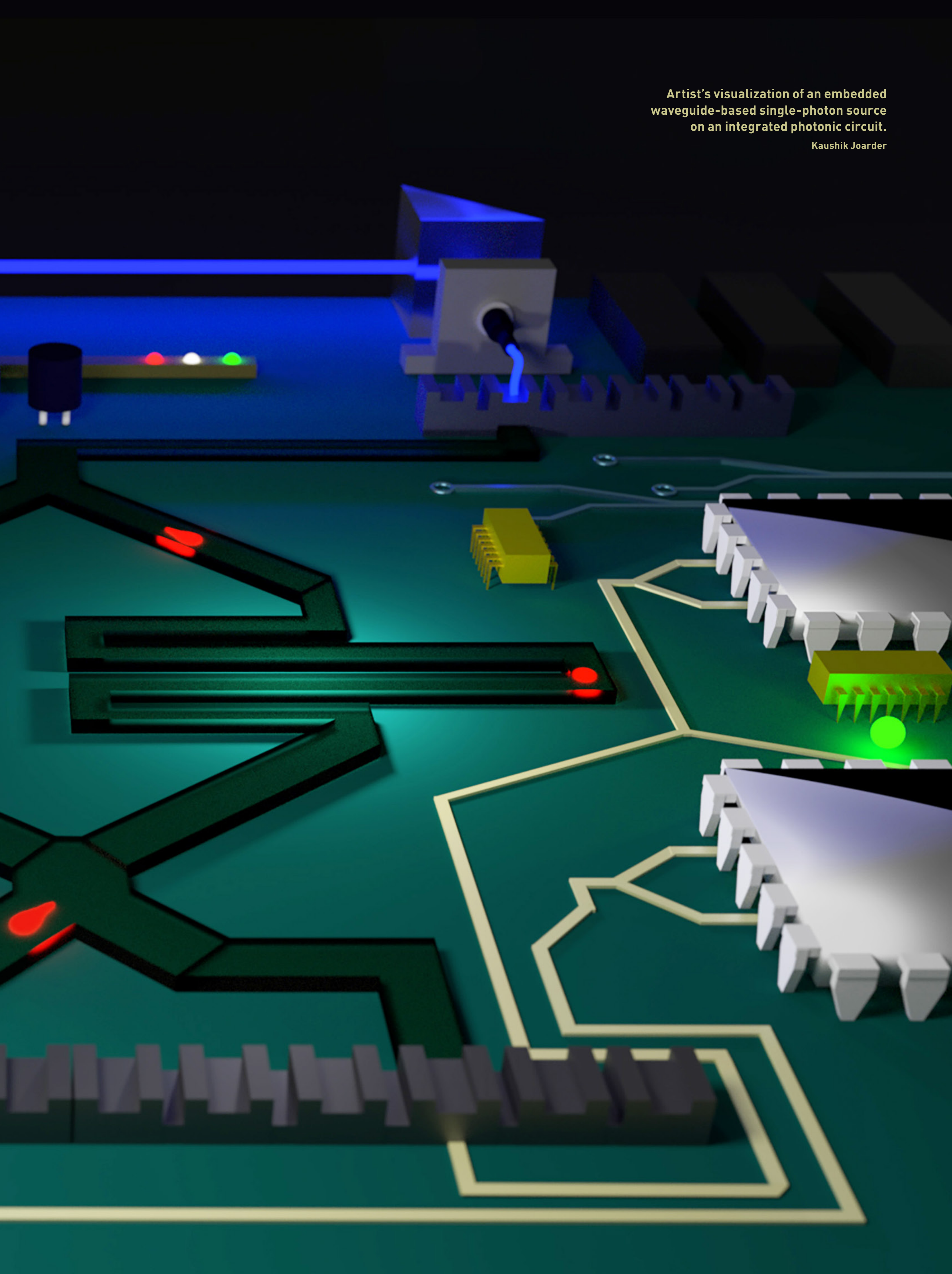

Artist's visualization of an embedded waveguide-based single-photon source on an integrated photonic circuit.

Kaushik Joarder

Just as the 19th century was labeled the machine age and the 20th century the information age, some are calling the 21st century the quantum age. And the past several decades have indeed seen remarkable developments in applying quantum physics to fundamental science and potential new technologies in communication, computation and sensing.

Optical testbeds have long been a popular choice for first tests to explore the quantum domain. This is primarily due to the inherent simplicity and beauty of optical demonstrations, as well as to their lower cost requirements versus some other systems, such as solid-state systems that carry high manufacturing costs and cryogenic measurement requirements. In optical implementations, quantumness can be seen at the detection level, and using photon-counting techniques we can demonstrate particle-like behavior for incident radiation.

True quantumness, however, is usually manifested when the source itself is also quantum. In optics, that would mean a single particle of light—one photon. In this feature, we take a look at the different types of currently available single-photon sources, their individual strengths and weaknesses, and their suitability for application in specific quantum technologies.

Useful quantum objects

Before diving into the details of single-photon sources, it is worth considering what photons are good for in quantum science and technology.

Photons, as chargeless, massless particles, interact very little with other neighbouring photons, and are easily manipulated and detected. As isolated entities, they can travel very far, and are thus perfect candidates as information carriers in quantum communication.

On the other hand, quantum computing requires quantum bits (qubits) and the building of quantum gates—and, while the polarization degree of freedom of a single photon leads to a good single qubit and suitable single-qubit gates, quantum gates are also needed to couple multiple qubits. This does not naturally happen with photons, as they don't naturally interact. However, there are ways to realize multiple-qubit gates with photons using light–matter interaction as an intermediary, or through other indirect processes such as heralded gates. Single photons are also popular tools in quantum metrology and quantum sensing.

Finally, no other technology or platform, perhaps, can compete with photons in usefulness as testbeds for foundational ideas and principles in quantum mechanics. Most of the seminal experiments in quantum foundations, many with intricate implications for quantum technologies, were first performed using photons, with those experiments paving the way for others using atoms, ions and molecules. These include the violation of the Bell inequality and various loophole-free versions of the same, other tests of non-locality, superdense coding, teleportation, entanglement swapping, steering, tests of weak measurements, and quantum cryptography, among many others.

Some key considerations

So single photons are eminently useful objects. But how does one generate a single photon? A natural first answer would be to take a strong light source and attenuate it until the mean number of photons in a given time frame reaches a number around 1 or less. Such a photon source—often called an attenuated laser source or weak coherent pulse (WCP)—is indeed a popular choice. But it is not truly quantum, as it exhibits different statistics from those a single-photon source would be expected to follow.

Choosing or designing the right single-photon source for a given application or experiment involves a number of other important considerations as well:

Availability. A key question is how readily available the photons are—or, in other words, whether single photons are available on demand, or only probabilistically. Many applications can work using probabilistic sources, but some require on-demand availability.

Entanglement. Also relevant to applications is whether the photons can be entangled, sharing the quantum correlation that makes them useful in many information-processing and communication protocols. Some single-photon generation schemes lend themselves to producing entangled photons more easily than others.

Brightness. For applications like generating secure keys for long-distance quantum key distribution (QKD), brightness plays a key role. Photons suffer losses as they travel over long distances, and thus the resultant key rate is high only when the original source can produce a relatively large number of photons per unit time.

Color. The emission wavelength and linewidth also matter for various applications. In communications, for instance, the 1550-nm telecom wavelength band is key for applications using optical fiber; in free space, on the other hand, we look for spectral ranges

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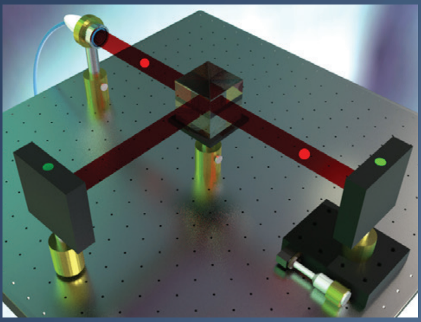
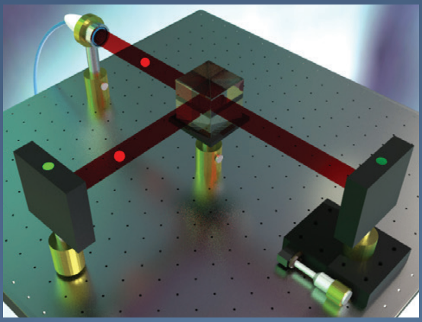
Characterizing single photons

While there are many techniques for generating single photons, it's also important to be able to confirm that single photons are indeed what's being generated. Two popular characterization techniques help with this verification.

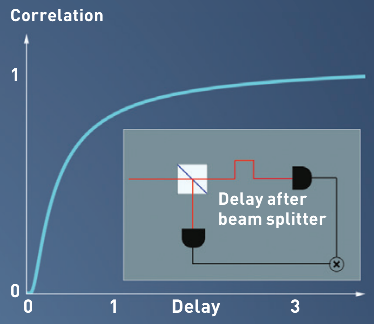
Antibunching: This technique relies on the fact that a single photon is an indivisible entity, and rests on the measurement of $g^{(2)}$, a second-order correlation function.



In the setup shown, a single photon is incident on one of the input ports of a 50/50 beam splitter, and the cross-correlation function is measured between the two detector outputs.

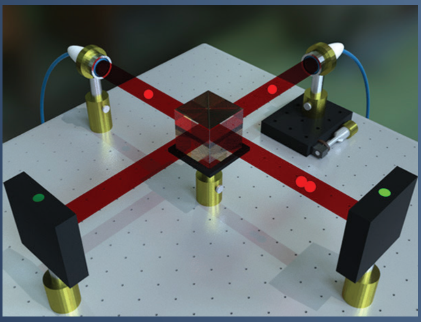


As the input is a single photon, it can exit from either of the output ports, but not through both, as a single photon does not split into two. Thus, both the detectors do not click simultaneously, and, at zero time delay, there is no cross-correlation between the two detector outputs.

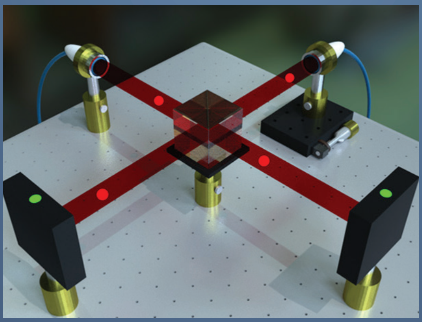


This leads to a dip at zero time delay and, gradually, to nonzero values for the cross-correlation as a function of time delay between the two detections. The value of $g^{(2)}(0)$—that is, $g^{(2)}$ at zero time delay—being as close to zero as possible is a signature of a true single photon source. (For comparison, for a laser source, $g^{(2)}(0) = 1$.)

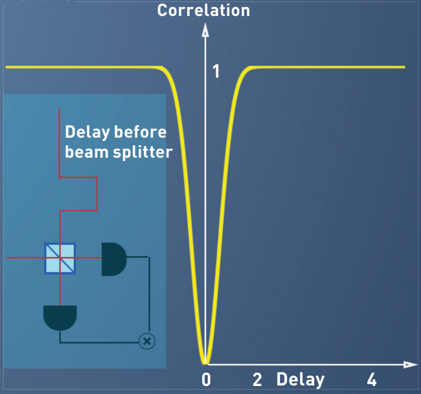
HOM bunching: In another common characterization tool for photon sources, this one based on the Hong-Ou-Mandel (HOM) effect, two completely indistinguishable single photons are incident on the two input ports (one in each input port) of a 50/50 beam splitter.



Because of second-order interference effects, only the possibility of both exiting photons reaching the same detector survives; by contrast, if one photon goes to each of the two individual detectors, they cancel out. This leads to the formation of a superposition state between the two 2-photon possibilities. When two indistinguishable photons are incident on two ports of a beam splitter, they always exit together at the same output port.

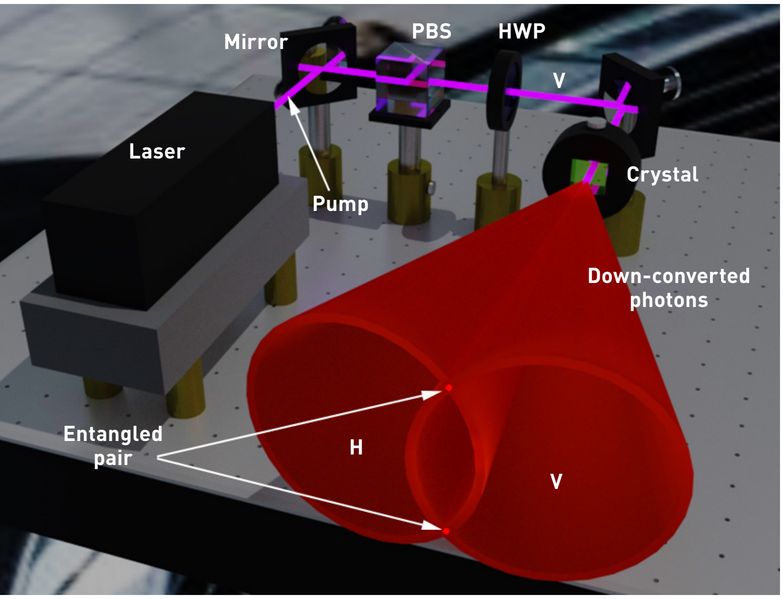


If there is some distinguishability factor—such as a slight delay in the arrival time between the two photons—there is chance that each will be reflected or transmitted and exit at different ports.



When a cross-correlation measurement is performed between the two output ports of the beam splitter, there is thus no correlation captured at zero time delay between the two input photons, with the curve gradually allowing nonzero correlation values with increasing time delay between the inputs—the HOM effect.

While both antibunching ($g^{(2)}$) and HOM bunching involve cross-correlation measurements between beam splitter outputs, the former method captures only the source's single-photon character, while the latter, in addition, characterizes the distinguishability between the input photons.



Type-II SPDC

In spontaneous parametric down-conversion (SPDC), a nonlinear medium (for example, a birefringent crystal), illuminated by a pump laser, facilitates a process in which a pump photon is absorbed to generate two correlated daughter photons, the signal and the idler. In so-called type-II SPDC, the signal and idler photons have perpendicular polarizations and emerge as two cones—with entangled photons found where the cones intersect.

where scattering is less prevalent and transmission is higher, generally in the near-infrared, telecom and other bands.

Purity and indistinguishability. Finally, how do we know that we have indeed produced a single photon? This is accomplished through one of several photon source characterization techniques, including $g^{(2)}$ measurement for purity and the Hong-Ou-Mandel (HOM) effect for indistinguishability (see p. 35).

Probabilistic single-photon sources

We can now look at some specific types of single-photon sources—beginning with those in which photon generation is probabilistic rather than on-demand.

Spontaneous parametric down-conversion (SPDC)

SPDC is the most popular means of generating single photons. In this second-order nonlinear optical process, a high-energy pump photon within a nonlinear optical medium generates two lower-energy photons, the "signal" and "idler" photons. As the name implies, the process is spontaneous (generated by quantum vacuum fields), parametric (the initial and final quantum-mechanical states of the medium are identical, and photon energy is always conserved), and an example of down-conversion (as the signal and idler frequencies are always lower than that of the pump).

The SPDC process obeys energy and momentum conservation, which are together known as the phase-matching conditions. SPDC can be used in so-called heralded schemes to generate single photons. As both photons are generated at the same time, detecting one heralds the presence of the other; this stream of heralded photons can then be used for single-photon applications.

SPDC has a number of key advantages. While the process efficiency is low, with only 1 in 10^9 or 10^{10} pump photons undergoing SPDC, the process still accounts for fairly bright photon sources with a wide range of applications, generating photons at a rate of about 2 MHz. In addition, SPDC excels in creating entangled photons; more than 99.5% fidelity of entanglement has been measured in entangled photons produced by the process. As a result, SPDC has found numerous applications in foundational tests of quantum mechanics, quantum information processing, quantum metrology and quantum communication.

One possible downside of SPDC—beyond its probabilistic nature, which makes it unsuitable for applications requiring photons on demand—is that SPDC carries a finite probability of multiphoton events. These can cause security loopholes in QKD protocols, although the situation is much better than with WCP sources, for which such probabilities are much higher.

Four-wave mixing

In another scheme for single-photon generation, four-wave mixing, two pump photons convert to a signal and an idler photon in the presence of a third-order nonlinear medium. Like SPDC, this requires satisfaction of phase-matching conditions. As opposed to SPDC, however, which can occur both in bulk and in confined geometries such as cavities and waveguides (which, in turn, narrows down the emission direction), four-wave mixing has generally been demonstrated only in integrated-optics structures involving waveguides.

Waveguide-based sources generally can have higher pair generation rates than bulk sources, due to a lower number of interacting modes. Four-wave-mixing-based photon sources have reported brightnesses of around 0.855 MHz, with a current record for entanglement fidelity of 99.7%.

“Artificial” atoms, or quantum dots, constitute one of the most promising photon sources on the near horizon, with much potential for future development and applications.

On-demand single-photon sources

Atom and ion sources

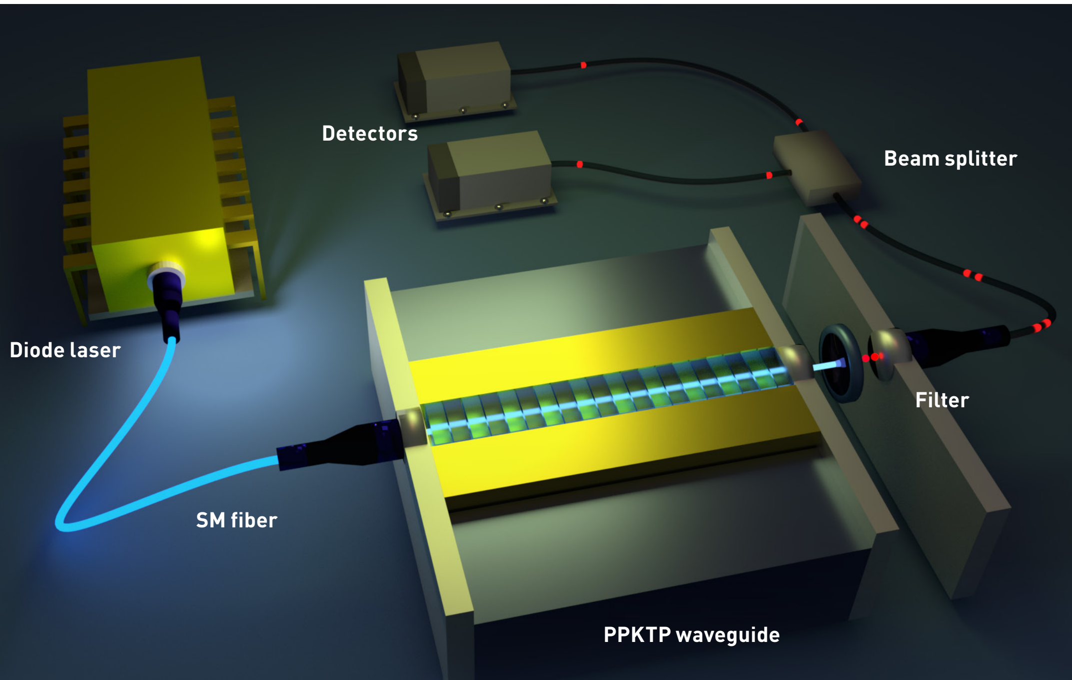
Among the simplest and most elegant architectures for single-photon sources involve photon emission due to transitions in atoms or ions. The first so-called single-photon source was an atomic-cascade-based source, and such sources were used in a number seminal experiments, such as demonstration of violation of the Bell inequality as well as double-slit interference using photons. The first antibunching experiment was successfully observed in resonant fluorescence of sodium atoms.

A single excited atom spontaneously emits a single photon. But isolating a single atom was historically a challenge. Then, the invention of ion trapping and atom trapping led to the investigation of trapped-ion and trapped-atom-based photon sources. Emission from such sources happens in all directions, which leads to poor detection efficiency. One way to boost the efficiency is to place atoms or ions in a cavity; in such a setup, the emission modes couple to the cavity mode, giving it directionality and thus increasing the efficiency.

An important advantage of trapped-atom and trapped-ion sources is the narrow emission linewidth that they offer. Thus they are very good in interferometric applications. They generate pure single photons, as the probability of multiple photon emission is quite low in general. While not the optimal choice for technological applications, they remain an excellent choice for experiments in quantum foundations as well as in metrology.

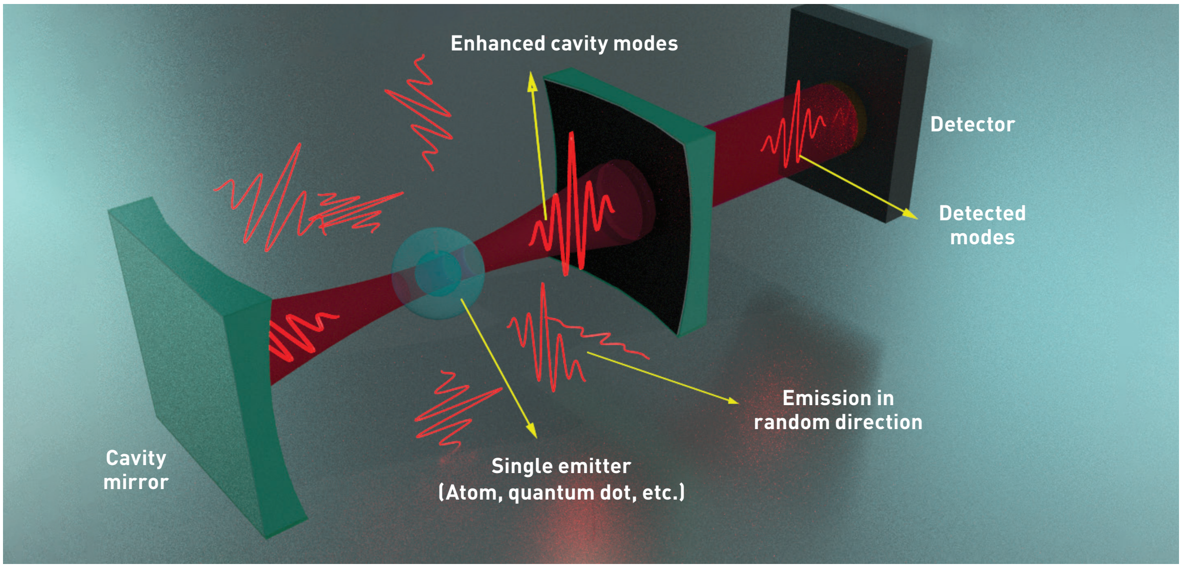
Quantum dots

“Artificial” atoms, or quantum dots, constitute one of the most promising photon sources on the near horizon, with much potential for future development and



Single photons in fiber

In this setup, a continuous-wave pump beam is coupled to a single-mode fiber. This fiber is aligned to a waveguide of periodically poled potassium titanyl phosphate (PPKTP), a popular nonlinear material. SPDC photon pairs (red bullets) are generated continuously and passed through a filter, which blocks any pump light. Photons whose polarizations are orthogonal to each other can be separated by a polarizing beam splitter and detected in two single-photon avalanche detectors.



Atoms in cavities

Both real atoms and "artificial atoms" (quantum dots), when excited, undergo spontaneous emission of photons in all directions. Atomic cascades and bi-exciton modes in quantum dots have short-lived metastable states and thus emit photons in pairs. Placing the atom or quantum dot in a cavity allows the emission modes resonant to the cavity to be enhanced, amplifying the emission in a given spatial direction.

applications. Quantum dots are tiny semiconductor particles or nanocrystals, with diameters in the 2-to-10-nm range. They are referred to as artificial atoms because of their atom-like discrete energy spectra.

When illuminated by an optical pulse, electrons in the quantum dot and its vicinity jump from the valence to the conduction band, leading to the formation of electron–hole pairs that then rapidly relax to the lowest energy states. Depending on the population, one can observe recombination from the exciton, the bi-exciton and multi-exciton states, labels that refer to the number of electron-hole pairs left to recombine. Although all such transitions possess distinct energies and can, in principle, serve as emitters for single photons by spectral filtering, the bi-excitonic and excitonic transitions are the most commonly used.

Quantum dot sources have also been used to produce highly entangled photon pairs. At present, the highest single-photon emission rate for quantum dots stands at 28.3 MHz, and an entanglement fidelity of 97.8% has been demonstrated. A quantum dot source can be either optically or electrically pumped. Electrical pumping holds the higher brightness record, and electrically pumped sources have even been realized at room temperature. On the other hand, the $g^{(2)}(0)$ for optically pumped quantum dot sources can be considerably lower than for electrically pumped ones—an indication that optical pumping may provide something closer to a true single-photon source.

Self-assembled quantum dots have been integrated with cavities to increase the directionality of emission and ease of use. The structural integrity of these cavities continues to improve, thereby enhancing the quality factor. Epitaxial deposition of quantum dots sometimes causes them to grow at random positions on a surface, which leads to losses in collection efficiency.

Continuous improvement is taking place in the quantum dot domain, with brightness and entanglement records being broken frequently. These deterministic sources have been successfully used in various QKD implementations as well as experimental demonstration of multiphoton Boson sampling, among other applications.

Diamond color centers

Another up-and-coming, promising quantum technology is based on color centers in carbon. In a diamond structure, missing carbon atoms can lead to defects in the crystal lattice, in which a single carbon atom is replaced with a combination of a nitrogen atom and a lattice vacancy. This is known as a diamond nitrogen–vacancy (NV) center. Other atoms in addition to nitrogen can also replace carbon atoms in such defects, which leads to a family of diamond color centers. NV centers in particular are promising candidates for single-photon generation. Moreover, since the emission rate has been shown to increase with temperature, they are potential candidates for room-temperature on-demand photon sources.

A great deal of work has gone into realizing and attempting to perfect single-photon sources. Yet they remain a research topic of considerable interest.

Bright future

Photons have been lead players in the research leaps that are setting up new quantum approaches to communication, metrology and computing. As a result, as the discussion above has suggested, a great deal of work has gone into realizing and attempting to perfect single-photon sources. Yet single-photon sources remain a research topic of considerable interest. What are the next steps?

Each of the sources that we have discussed here has room for at least some improvement. While some are comparatively established and near their optimal performance, others hold more scope for further research and the establishment of new records in brightness, entanglement fidelity, stability, efficiency and indistinguishability of photons.

Even as researchers work on improving those parameters, many also look forward to a future quantum internet, in which the entire communication network is replaced with a quantum version—with satellites transmitting photons to Earth and breaking distance barriers; with optical fibers connecting far-away nodes to form backbone networks; with quantum memory becoming more advanced and capable of storing vital quantum information. Photons will also play a big role in quantum computing, both as an information carrier in hybrid schemes and as the basis for linear-optics-based quantum computing.

Last but not the least, even as the quantum community continues to push forward these far-reaching technologies, quantum mechanics and quantum optics continue to fascinate, creating a stream of intriguing new questions that need to be tested and verified through precision experiments. What better candidate for running such tests than a single photon? OPN

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The author has posted a detailed list of references at ***www.rri.res.in/quic/resources/opn2019***.

Single-photon sources compared

	SPDC	Atoms and ions	Quantum dots	NV centers	Four-wave mixing
Probabilistic/ Deterministic	Probabilistic	Probabilistic, Deterministic	Deterministic	Deterministic	Probabilistic
Emission range	600–1700 nm	Transition lines	IR, telecom	600–800 nm	600–1550 nm
Bandwidth	nm	10 MHz	nm	1–100 nm	10 nm
Operating temperature	273–473 K	Room temp., mK (in cavity)	Room temp., cryogenic	300–500 K	Room temp.
Emission direction	Narrow	Random, narrow	Random, narrow	Random	Narrow
Efficiency max.	0.84	0.88	0.97	0.35	0.26
Brightness	2.01 MHz	55 kHz	28.3 MHz	850 kHz	855 kHz
Best $g^{(2)}$	0.004	0.0003	0.000075	0.07	0.007
Entanglement fidelity	0.9959	0.93	0.978	---	0.997
HOM visibility	0.99	0.93	0.9956	0.66	0.97
Quantum applications	Metrology, information, foundations, communications	Foundations	Foundations, communications	Communications, networks	Integrated photonics

For references, footnotes and important additional information on this table, see the version posted by the author at **www.rri.res.in/quic/resources/opn2019**