SEMICONDUCTOR SINGLE-PHOTON SOURCES: PROGRESSES AND APPLICATIONS

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Single photons are the cornerstones of many applications in quantum technologies, from quantum computing to quantum networks. A new technology for the generation of single-photons has recently emerged, allowing a ten-time increase in efficiency with near-unity quantum purity. These single-photon sources are based on semiconductor quantum dots in optical microcavities.

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LIGHT IN QUANTUM TECHNOLOGIES

Light, and more precisely quantum light is a key component of the emerging second quantum revolution. Like in classical technologies, light is the ideal support to carry the quantum information from one place to another and develop quantum communications. Such communication is highly sought after as it admits confidentiality guarantees that rely only on the most fundamental laws of physics. They can also be used to network several quantum processors leading to strong increases in computational capabilities. Actually, quantum light is also a highly promising technology for developing a quantum computer, with the unique advantage that photons are non-interacting particles in vacuum and barely suffer from decoherence. This potential is reflected by the creation of start-up companies with the objective of developing the first optical quantum computing machines in the last few years like PsiQuantum in the United States or Xanadu in Canada which have raised several hundreds of millions of dollars, and more recently with QUIX, ORCA computing, and Quandela in Europe, among others. Finally, quantum light can be used to push the limits of sensing, a possibility beautifully illustrated by the introduction of squeezed light in gravitational waves interferometers.

A very appealing property of quantum light for all these applications is that it offers many degrees of freedom to encode the quantum information: wavelength, polarization, path, orbital angular momentum, time… It also makes it possible to encode more than one quantum bit on a single light wavepacket. These possibilities have also led to different approaches to manipulate the quantum information. Some approaches encode the information on single photons (discrete variables), others exploit quantum modes (continuous variables). In the following, we discuss approaches based on discrete variables, an approach where first small-size quantum computing processors have been demonstrated with a defined path toward a universal quantum-computing machine.

SINGLE-PHOTON SOURCES – FIGURES OF MERIT

The ideal single-photon source (SPS) produces light pulses with exactly one photon — no more, no less — in a well-defined spectral and spatial mode of given polarization. In real

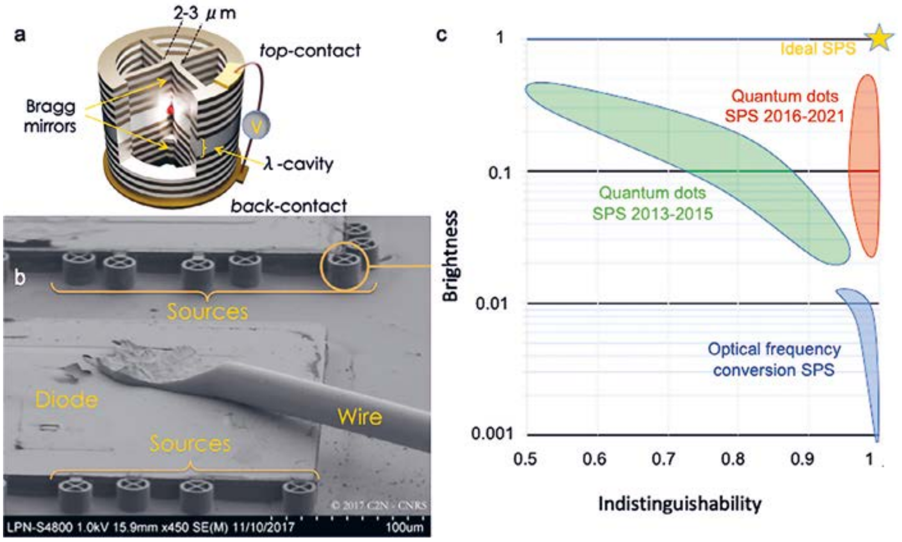

Figure 1. (a) Schematic of single photon source based on an electrically controlled quantum dot in a cavity. (b) Scanning electron microscope image of a semiconductor chip with 11 single photon sources. (c) State of the art in Single Photon Sources (SPS) technologies. The various technologies are presented on a 2D map corresponding to the source brightness and indistinguishability. An ideal source would be at the upper right corner. From 2013 to 2015, important progresses were reported on QD-based single photon sources, but they were either bright or indistinguishable. Since 2016, it is possible to combine both properties.

life, there is always a probability that the light pulse contains more than one photon or no photon at all. A single-photon source is thus characterized by the probability to actually have one photon per pulse, also called the source brightness, as well the probability to have no more than one photon, also called "single-photon purity".

The final criteria, *i.e.* that the same spectral mode is always produced must be understood at the quantum level. In the spectral domain, the single-photon pulse is a quantum superposition of single photon states of various frequencies with complex coefficients: the source should produce always the exact same superposition. This property is crucial for quantum technologies as it allows the implementation of photon-photon gates both for quantum computing or quantum communications. The effective photon-photon interaction relies on a very fundamental quantum effect called "quantum interference": when two single-photon pulses in exactly the same spectral mode are sent at the two inputs of a beam splitter, the two photons will bunch and exit together through the same beam-splitter output, a situation very different from what we would expect from a classical perspective, by which we would expect that with some probability the photons exit by separate outputs. This property, which is used to build two-photon gates with beam splitters, waveplates and detectors, arises from the impossibility of distinguishing the single-photon pulses. A single-photon source is thus also characterized by its degree of indistinguishability.

The early development of optical quantum technologies has relied on single-photon sources based on optical frequency conversion: a laser pulse sent on a non-linear crystal generates photon pairs. The system operates at the threshold for photon-pair generation where most of the time no pair is produced and the probability of generating two pairs is kept below 1%. To operate such source, one photon of the pairs is detected to announce the presence of the other one. Such a source is intrinsically limited to very low brightness (B<1 %), setting strong limitations for scalability.

A NEW GENERATION OF SINGLE-PHOTON SOURCES

In the last few years, a new technology for single-photon sources has emerged based on semiconductor quantum dots (QDs): a nano-insertion of InAs in GaAs. In these nanostructures, electrons (and holes) present discrete energy levels like in a single atom. In 2000, these artificial atoms have been shown to emit single-photons based on the recombination of electron-hole pairs at temperatures around 5 K [1]. To efficiently collect the single photons that are otherwise emitted in all directions of space, the QD is inserted in an optical microcavity that confines light in a volume of the order of λ^3. Fig. 1a presents the ● ● ●

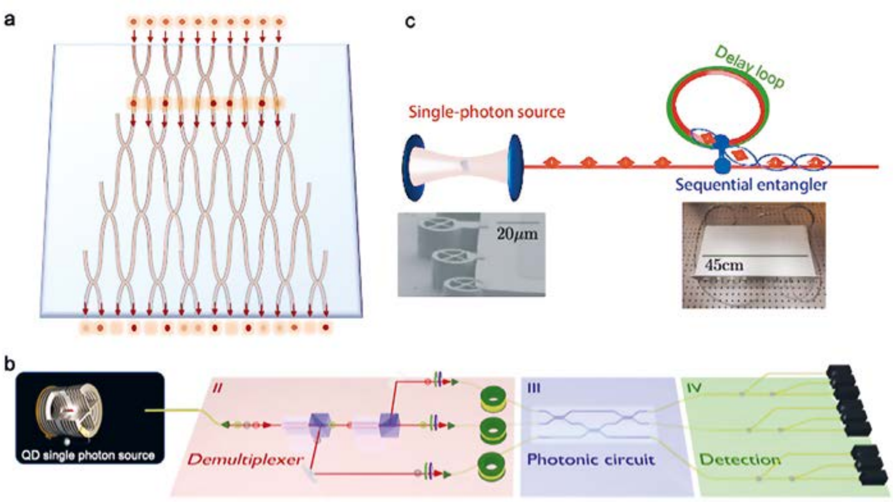

Figure 2. (a) Schematic of an intermediate quantum computing scheme: Boson Sampling. (b) Interfacing a QD single-photon source with a photonic chip to implement a 3-photon experiment. (c) Scheme used to develop light states comprising several entangled single photons from a QD single-photon source.

architecture of such a source where the QDs are precisely positioned at the center of a cavity based on two Bragg reflectors that confine light in the vertical direction. The wheel-shaped structure in the transverse direction confines light in its center, by refractive index contrast. Finally, the device embeds a diode structure that allows controlling the electric field around the QD. To do so, the device is connected to a bigger surface where an electrical contact is defined and a wire bounded (Fig. 1b).

The insertion of the QD in a cavity has multiple effects: first it allows accelerating the emission process into the cavity mode, so that the photons are preferentially emitted in this direction. Single photon sources with a record brightness around 80 % have been demonstrated with this approach in 2013 [2]. Second, it shortens the time the electron-hole pairs remain in the QDs before emitting a photon. This is crucial to obtain indistinguishable photons by strongly reducing the time where the system is subject to the randomness of the semiconductor environment: charge noise, vibrations, *etc.* The charge noise is further suppressed by applying a bias on the diode structure that allows sweeping away any unwanted charge. Combining these various techniques with a resonant excitation approach to perform coherent control of the artificial atom led to a new generation of sources in 2016 [3,4]. These sources were able to produce single photons with a near-unity indistinguishability with brightness in the B = 10–20 % range. These sources were more than ten times brighter than sources based on frequency conversion for the same degree of indistinguishability (Fig. 1c). Such increase allows a spectacular scaling of optical quantum technologies since the availability of N single-photon qubits scales as B^N.

Since then, the quality of sources has continued improving reaching B>50 % in 2021. In 2019, it was also shown that such devices can provide new types of photonics quantum bits, where the information can be encoded on the photon number [5]: arbitrary quantum superposition of 0 and 1 photon were generated by transferring the coherence that is optically imprinted at the level of the atom to the emitted field.

FIRST APPLICATIONS IN OPTICAL QUANTUM COMPUTING

This new generation of sources has immediately been used to gain important speed-up in some specific quantum-computing tasks. Boson sampling is an intermediate quantum-computing scheme that has been proposed as a path to demonstrate quantum computational advantage. It relies on sending N-single photon quantum bits in a random optical circuit, where the single photons undergo many steps of quantum interferences. At the end of the network, single-photon detectors measure the photon distribution (Fig. 2.a). Predicting the output distribution has been shown to be a computationally hard problem, inaccessible to today's most powerful super-computers as soon as the number of photons would slightly exceed 50. The new generation of single-photon source discussed above led to a 10^3-10^6 speedup of Boson Sampling computing schemes in 2017 with 3-5 photonic qubits [6]. In 2019, the group of Chao-Yang Lu in Hefei University in China brought this number to 20 qubits, using a very similar source technology as the one presented here, setting an unprecedented record in discrete variable optical quantum computing [7].

The above achievements were obtained with optical circuits implemented in free space, with many mirrors, beam splitters, etc, making the approach hardly scalable. However, optical quantum computing can be realized with a fully integrated approach, where single photon sources and detectors, inserted in cryostats to operate in the 2-10 K range, are fiber-pigtailed and fiber connected to photonic chips where the photonic quantum bits are manipulated at room temperature.

QD single photon sources have been used for a first proof of principle for on-chip quantum computation (Fig. 2.b) [8]. The source generates temporal trains of single-photon quantum bits at a clock rate around 80 MHz. A temporal to spatial demultiplexer is used to convert a train of N photons in time, into an input of N photons at the N entries of a photonic chip. The integrated photonic circuit was obtained by femto-second laser writing in glass, a technology that allows very low guide and insertion losses. In this first demonstration, three photons were manipulated at unprecedented rates on chip.

The QD sources are also very interesting from the perspective of creating new photonic states in which several single photons are entangled [9].

Some of these states, such as the so-called "cluster-states" are an important universal resource quantum computing, which offer a scalable path to large-scale, fault-tolerant quantum computing. To obtain such a state, the single photons that are sequentially generated by the source are sent into an entangling apparatus that fits into a simple rack-size box (Fig 2.c). The photons are sent onto an optical gate based on a beam splitter that entangle the second photon with the first emitted one that has been partially stored into a fiber loop. Repeating the scheme with as many photons as desired can be used to generate such photonic cluster state with an arbitrarily high number of photons and was recently demonstrated to entangle 4 photons in a linear cluster state.

FUTURE OPPORTUNITIES

The new generation of single-photon sources based on semiconductor quantum dots open exciting perspectives for optical quantum technologies by providing a disruptive technology on the photon generation side. A similar breakthrough was obtained almost a decade ago on the single-photon detector side with detection efficiency now routinely above 90 %. The commercialization and industrialization of these sources has begun, developing robust and easy-to-use products for the researchers and engineers developing quantum technologies. The best sources currently operate in the 890-950 nm wavelength range. New developments should soon bring this technology to the 700-850 nm range, with great potential for interfacing with atomic-based quantum memories for instance. Finally, the same sources could in the future be used to directly generate photonic cluster states, with unparalleled efficiency.

This relies on exploiting the spin degree of freedom of an electron in a QD. This is the next breakthrough that the quantum dot scientific community is pursuing, a milestone that would open the way toward scalable quantum computing, long distance quantum communications as well as new limits in optical sensing. ●

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