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QUANTUM OPTICS

The race for the ideal single-photon source is on

The careful optimization of all components of a quantum emitter single photon source yields over 50% end-to-end efficiency, a benchmark for optical quantum technologies.

Sarah Thomas and Pascale Senellart

The development of highly efficient and perfectly controlled building blocks for quantum technologies is becoming an increasingly important topic. Single-photon sources are one such building block, since quantum light is not only central to quantum communication, but also to remote quantum computing as well as sensing. The ideal single-photon source is a device that delivers wavepackets of light in a clocked manner, where each wavepacket contains exactly one photon in a pure quantum state. Purity is critical to ensure that photon–photon gates can be implemented through quantum interference with high fidelity, and efficiency, that is the probability to have a photon per clock cycle, is vital for scalability. In their work reported now in *Nature Nanotechnology*[1], Natasha Tomm and co-workers demonstrate an overall efficiency of 57%, while maintaining state-of-the-art quantum purity.

Over the past 20 years, two distinct technologies for single-photon sources have been explored. The first, heralded approach is based on frequency conversion in a non-linear crystal: photon pairs are produced randomly, and the detection of one photon of the pair announces the availability of the other photon for processing. Such schemes present the very attractive feature of room temperature operation and simplicity. However, high quantum purity is only obtained at very low pair generation probability so that the overall efficiency is inherently low, below a few percent. The other approach is based on single quantum emitters, an atom-like system that intrinsically emits one photon at a time. Such an approach can in principle lead to near-unity efficiency at high quantum purity but requires highly sophisticated techniques to collect the photons.

In the past four years, important progress in single-photon sources based on semiconductor quantum dots has started reshaping the landscape of optical quantum technologies. An increasing number of groups have obtained near-unity quantum purity for quantum dots in optical cavities, with an overall efficiency at least 10 times higher than that of heralded sources[2]. Such quantum dot sources are now commercially available and are accelerating progress in intermediate scale quantum computing, one example being the demonstration of a 20 photon Boson sampling protocol[3]. However, the sources have still been limited to around 25% overall efficiency, so that three times out of four, the expected clocked single photon is missing.

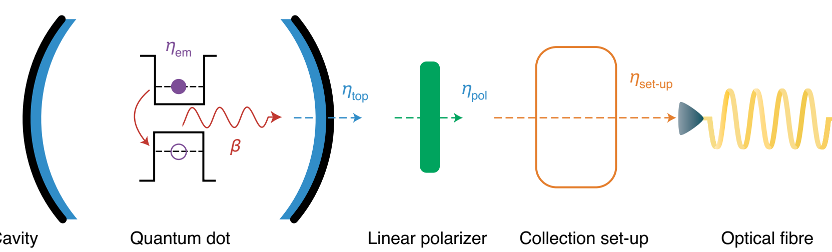

Fig. 1 | Working principle of a quantum emitter single photon source. The efficiency of the source depends on many parameters including the probability of exciting the emitter η_{em}, which then emits a single photon into the cavity mode with probability β. The photon exits the cavity mode with probability η_{top}, undergoes polarization filtering η_{pol}, and finally is coupled into a single mode fibre with efficiency $\eta_{set\text{-}up}$.

To capture the tour de force by Tomm and colleagues to achieve 57% end-to-end efficiency, let us consider the numerous parameters that control the source performance. These ingredients are sketched in Fig. 1. For each clocked laser excitation, the quantum dot is brought to the desired excited state with a population probability η_{em}. Coupling the dot to an optical microcavity accelerates the spontaneous emission via the Purcell effect and the single photon is emitted into a defined mode with probability β. The accelerated emission into the cavity mode is realized in the bad cavity limit, where the single photon rapidly escapes the cavity through the desired port with a probability η_{top}. Optical quantum technologies require single photons with a well-defined polarization, so polarization filtering is required with probability η_{pol}. All these parameters determine the probability to obtain a single photon at the cavity output, $P_{out} = \eta_{em}\beta\eta_{top}\eta_{pol}$. An additional experimental apparatus, comprised of lenses, mirrors, beam shapers, filters and so on is finally needed to couple the photon stream to a single mode fibre with efficiency $\eta_{set\text{-}up}$. The overall probability to obtain the single photon per clock cycle at the output of the fibre is $P_{fibre} = P_{out}\eta_{set\text{-}up}$.

In the past decade, the quantum dot community has pushed every single parameter to very high values: rapid adiabatic passage techniques enabled near-unity η_{em} (ref. [4]), very high β was demonstrated with various photonic structures, where micropillar or bullseye cavities showed the best extraction efficiency of $\beta \times \eta_{top} \approx 0.8$ (refs. [5,6]). Resonant excitation schemes allowed indistinguishability values above 0.995 (refs. [7,8]). However, this was reached in schemes requiring strong polarization filtering ($\eta_{pol} < 0.5$). Recently, the implementation of a polarized acceleration of spontaneous emission with a birefringent cavity overcame this limitation[9].

To obtain $P_{fibre} = 0.57$, Tomm and co-workers made use of an open cavity structure (Fig. 2) where the cavity bottom mirror is grown below the cavity spacer that embeds the quantum dots. Open cavities enable controlled coupling to quantum dots, with the mirror directly carved into the tip of a fibre[10]. Here, the top mirror is made of a laser-etched silica plate with

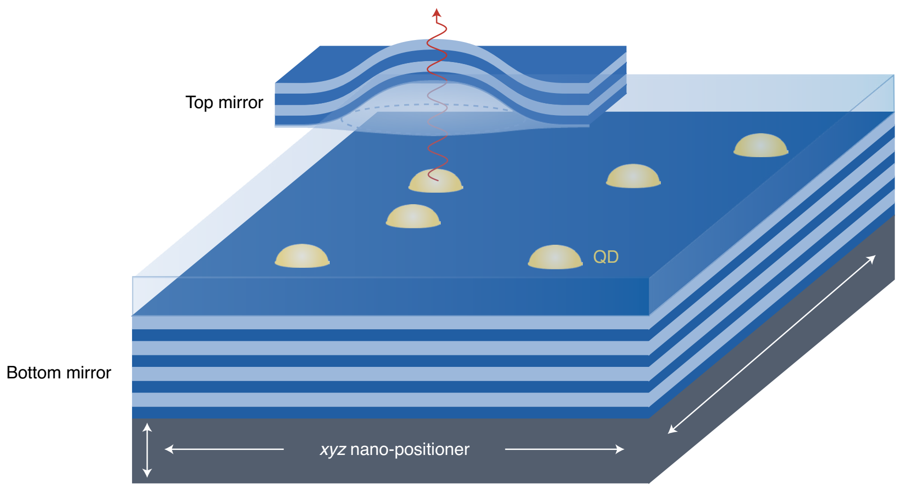

Fig. 2 | Efficient single photon source. The experimental implementation by Tomm and co-workers[1] is based on a quantum dot (QD) coupled to an open cavity. The researchers optimize the position of the QD and tune the cavity frequency by means of the *xyz* positioner. Outcoupling of single photons proceeds via the top mirror.

dielectric mirror coating. Since quantum dots grow with random spatial locations and spectral frequencies, the open cavity structure offers the ability to move the sample plane to centre a given quantum dot in the cavity, and to adjust the distance in the orthogonal direction to finely tune the cavity frequency to the dot transition. Strain in the semiconductor material generates birefringence in the cavity and leads to a polarized acceleration of spontaneous emission. Finally, the researchers position the first lens of the collection apparatus just above the top cavity mirror and place the overall structure in a low vibration liquid-helium bath cryostat. With such an in situ optimization of the emitter–cavity coupling, Tomm et al. reach near state-of-the-art values for most parameters simultaneously. The increase in efficiency with respect to the state of the art by an overall factor of two depends mainly on the improvement of two parameters. The researchers reduce the cavity losses to achieve $\eta_{\text{top}} = 0.97$ and increase the set-up efficiency to reach $\eta_{\text{set-up}} = 0.69$.

Until now, the race for the most efficient source of indistinguishable single photons was led by the micropillar cavity approach[3], which will require improved cavity designs to match the new record. However, the possibility to integrate the fibre directly on top of a micropillar source in a fully monolithic structure[11] puts them in a very good position to be operated in a standard closed cycle cryostat. These cryostats are already used for single-photon detectors based on superconducting nanowires and could ensure a wide use of the technology. The integration of the open cavity approach in such cryostats will demand fine engineering of the vibration damping to control the cavity resonance, but there is no doubt that the industry of ultra-low vibration cryogenics could address this challenge!

This experimental realization not only represents the accumulation of a decade of progress in quantum dot based light sources, but marks a new step for quantum technologies based on single photons. While the number of groups adopting quantum dot sources slowly increases, the community developing optical quantum technologies has long relied on heralding to build their protocols. With this new step, the probability to get a single photon on demand approaches the standard heralding efficiency, a threshold where the advantage provided by heralding simply disappears. These results also approach another milestone, by bringing the combined source–detector efficiency closer to the 2/3 threshold — this threshold is required for the scalability of optical quantum computing[12]. No doubt, this work will stimulate further technological developments and it gives the go-ahead for the next stage in the race toward the ideal single-photon source. ❐

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References

1. Tomm, N. et al. *Nat. Nanotechnol.* https://doi.org/10.1038/s41565-020-00831-x (2021).
2. Senellart, P., Solomon, G. & White, A. *Nat. Nanotechnol.* **12**, 1026 (2017).
3. Wang, H. et al. *Phys. Rev. Lett.* **123**, 250503 (2019).
4. Simon, C.-M. et al. *Phys. Rev. Lett.* **106**, 166801 (2011).
5. Gazzano, O. et al. *Nat. Commun.* **4**, 1425 (2013).
6. Liu, J. et al. *Nat. Nanotechnol.* **14**, 586 (2019).
7. Ding, X. et al. *Phys. Rev. Lett.* **116**, 020401 (2016).
8. Somaschi, N. et al. *Nat. Photon.* **10**, 340–345 (2016).
9. Wang, H. et al. *Nat. Photon.* **13**, 770–775 (2019).
10. Muller, A. et al. *Appl. Phys. Lett.* **95**, 173101 (2009).
11. Snijders, H. et al. *Phys. Rev. Appl.* **9**, 031002 (2018).
12. Varnava, M. et al. *Phys. Rev. Lett.* **100**, 060502 (2008).

Competing interests

P.S. is the co-founder and chief scientific officer of Quandela.