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Quantum dots get a bright upgrade

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Abstract

Developing a bright, deterministic source of entangled photon pairs has been an outstanding scientific and technological challenge. Semiconductor quantum dots are a promising candidate for this task. A new device combining a circular Bragg resonator and a piezoelectric actuator achieves high brightness and entanglement fidelity simultaneously, overcoming previous limitations. This breakthrough enhances quantum dot applications in entanglement-based quantum communication protocols.

Scalable sources of entangled photons are the keystone for realizing photonic quantum networks and enabling entanglement-based quantum communication protocols. Currently, most sources are based on the spontaneous parametric down-conversion (SPDC) process, which are fundamentally limited by their probabilistic photon emission, hindering their scalability and widespread adoption.

Semiconductor quantum dots have emerged as promising candidates to overcome these limitations (see Fig. 1). Quantum dots can generate polarization-entangled photon pairs on-demand^{1,2}, with high photon flux, indistinguishability, and entanglement fidelity³. However, the key challenge has been that optimizing different figures of merit, like brightness (extraction efficiency or photon pair rate per excitation pulse) and entanglement fidelity, often requires different technological solutions that are difficult to be integrated into single devices.

Previous efforts illustrate these trade-offs. Dousse et al.⁴ increased the photon pair generation rate to 0.12 per excitation pulse by coupling quantum dots to micropillar photonic molecules⁴. This was further pushed to 0.65 by Liu et al.³ by using quantum dots embedded in circular ring gratings³. However, the lack of tunability in these devices limited the achievable entanglement fidelity. Work from Huber et al.⁵ used strain-tuning to generate highly entangled photon pairs from GaAs quantum dots, with fidelities up to 0.98, but at the cost of modest brightness⁵.

Attempts at combining brightness enhancement and entanglement optimization proved difficult. Now, a team of researchers from Sapienza University of Rome, Johannes Kepler University Linz, and the University of Würzburg have successfully developed a powerful device that overcomes this long-standing conundrum. Their approach, described in a recent paper in *eLight*⁶, combines two cutting-edge technologies - a circular Bragg resonator structure⁷ that enhances the brightness of the quantum dot emission, and an integrated piezoelectric actuator⁸ that allows precise tuning of strain fields⁹ to maximize the entanglement.

This is a beautiful demonstration that both high brightness and high entanglement can be achieved simultaneously from a quantum dot based entangled photon source. This device can emit entangled photon pairs with fidelities up to 0.96, very close to the maximum value, while still maintaining a photon pair rate of 0.69.

The key was optically positioning and then embedding the quantum dot inside a specially engineered circular Bragg grating resonator. The fabricated photonic structure accelerates the dot's emission via Purcell enhancement and funnels a large fraction of emitted photons into a collimated beam, building on earlier works like that of Davanco et al.⁷ and Liu et al.³. Simultaneously, finely controlled strain fields from the piezoelectric actuator allowed canceling out the energetic fine structure splitting that normally scrambles the photon entanglement, similar to the approach used by Plumhof et al.¹⁰.

This breakthrough, based on the hybrid resonator-actuator approach, directly tackles the long-standing

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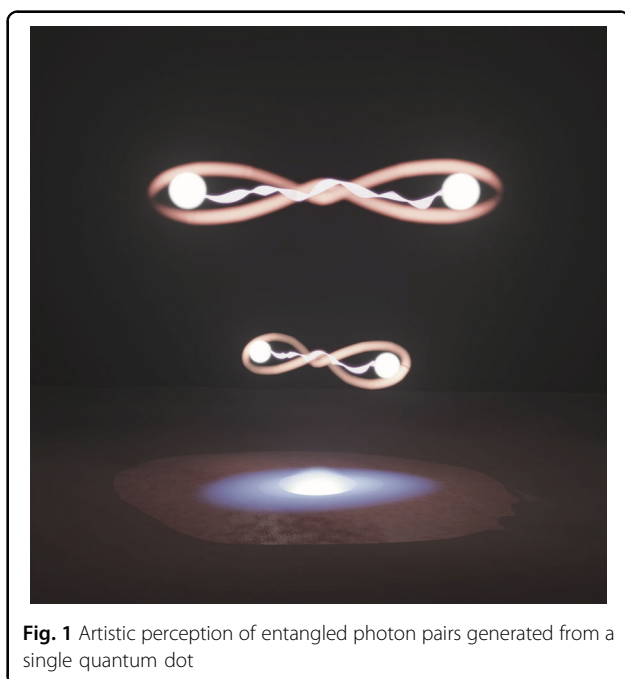


Fig. 1 Artistic perception of entangled photon pairs generated from a single quantum dot

challenge of simultaneously optimizing brightness and entanglement for quantum dot sources, and may finally lead to a source that checks all the boxes, i.e., high brightness, high fidelity entanglement, and even high single photon indistinguishability. This is crucial for enabling the exploitation of semiconductor quantum dots in entanglement-based quantum network protocols.

Although the device has reached a very high level of complexity and functionality, there is still great potential for improvement. The strain tuning range can be significantly improved by thinning down the GaAs nanomembrane that contains the quantum dots. The single photon indistinguishability can be boosted further by stabilizing the charge environment and reducing spectral wandering with a charge tunable diode¹¹, and moreover, by controlling the timing correlations between the entangled photon pairs¹². Non-zero multiphoton emission probabilities and residual components in the reconstructed density matrix may also be improved in future devices. To fully harness the potential of this semiconductor platform, one should also consider including electrical injection (in order to replace the bulky laser excitation setups)^{13,14}, and/or integrating full electrical control to tune the wavelength of entangled photons as demonstrated recently by Chen et al.¹⁵. Among the next steps, realizing entanglement swapping^{16,17} with two remote sources would be a key experiment to prove the scalability of quantum dots based sources.

From early work on micropillar photonic molecules to the latest electrical wavelength-tuning capabilities, the multi-decade quest to unleash the potential of semiconductor quantum dots as entangled photon sources has seen steady progress. The focus of the community is gradually shifting from physics curiosity to useful quantum technology out of the lab^{18–21}. We believe that quantum dots will truly become an enabling technology for realizing quantum networks and all their revolutionary applications.

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Conflict of interest

The author declares no competing interests.

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