Scaling up solid-state quantum photonics

Radiative coupling creates an entangled state between two silicon vacancies in diamond

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Scaling-up solid-state quantum photonics

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A deterministic interface between a single atom and a single optical photon is the essential building block underpinning many quantum applications of light for quantum communication, sensing, and simulations. Unfortunately light and matter interacts weakly with each other, so the challenge is to create conditions where such strong interaction can be obtained. Solid-state quantum photonics has matured dramatically recently, and today it is possible to create artificial photonic nanostructures that dramatically enhance light-matter coupling. Moreover, single atoms that are cumbersome to control experimentally since they need to be trapped and cooled, can be replaced by solid-state quantum emitters such as vacancy centers in diamond, molecules, or quantum dots [1, 2]. The high quality and purity of these systems now imply that coherent and near-deterministic photon-emitter interfaces are routinely constructed [2]. A remaining challenge is to scale up and deterministically couple multiple quantum emitters. The paper by Evans et al. [3] reports on the successful coupling of two solid-state quantum emitters mediated by their mutual coupling to a nanophotonic cavity. Figure 1 illustrates that the radiative coupling leads to the formation of an entangled state between the two emitters. The experiment opens new avenues for solid-state quantum photonics.

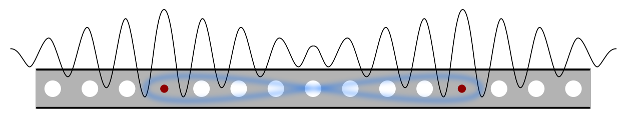

Figure 1: Illustration of two solid-state quantum emitters (red dots) that are mutually entangled by their strong radiative coupling mediated by a photonic nanostructure. The indicated oscillating wavepackets illustrate the spatial extend of the electromagnetic field radiated by each emitter. Courtesy of Xiao-Liu Chu.

The essential figure-of-merit for a photon-emitter interface is the cooperativity C. It quantifies the probability that a narrow-bandwidth single photon launched in a nanophotonic waveguide or cavity will interact with the emitter: $P = C^2/(1+C)^2$. C is maximized by decreasing the interaction volume, reducing loss of the resonator, or by suppressing spontaneous emission leakage or other decoherence processes. $C \gg 1$ is the limit of a deterministic photon-emitter interface. Steady progress of solid-state systems has led to the demonstration of an extremely high cooperativity ranging to several hundreds for the case of self-assembled quantum dots. Evans et al.[3] reports an impressive improvement of cooperativity for silicon-vacancy centers in a diamond nanocavity by more than an order of magnitude over previous work [4] to reach $C \sim 20$. The cooperativity determines the obtainable fidelity of, e.g., photon-photon quantum gates and quantum nonlinearities that can be mediated with a deterministically coupled emitter [5]

The ultimate challenge in quantum science and technology of today is to scale-up the emergent quantum hardware in order to produce and control many quantum bits (qubits). Importantly, current state-of-the-art photon-emitter interfaces can produce very long strings of photonic qubits, and by controlling a coherent ground state spin the photons can be created on-demand in a multi-photon entangled state [6]. However, it remains an essential challenge to scale up these systems to couple multiple emitters. This enables the generation of more advanced photonic resources than merely a single string of photonic qubits. The main challenge is to overcome inhomogeneities due to, e.g., structural differences between emitters or internal strain. In Evans et al. [3] such intrinsic inhomogeneity is combatted with magnetic field tuning and pre-selection of near-identical emitters. With this approach they were able to demonstrate entanglement between two silicon-vacancy color centers in a diamond nanocavity and to controllably couple the spin ground states. This work could be extended to a semiconductor platform where advanced device engineering capabilities would allow local tuning of each quantum emitter, e.g., with a local electric field [7]. It is an exciting future challenge to explore how many emitters that can be controllably coupled with such methods.

Even few efficiently coupled quantum emitters have exciting applications. Hence a single ground-state spin in an emitter can be employed for a quantum gate operation on another spin stored in a coupled emitter. While the manipulation of a single spin in a quantum emitter enables multi-photon entanglement generation, the addition of a spin-spin gate operation could lead to the deterministic preparation of arrays of multi-photon entangled states, notably 2D photonic cluster states [8]. This constitutes a universal resource for measurement-based quantum computing, where the general approach is to prepare a multi-qubit entangled state and subsequently implement quantum algorithms by carrying out only single-qubit measurements on the entangled state [9]. Another exciting application area is within quantum communication, where the outstanding challenge is to construct a quantum repeater that may allow distributing quantum information over long distances in the presence of unavoidable loss. Interestingly, all-photonic quantum repeaters have been proposed where quantum information is encoded and protected in multi-photon entangled states [10]. Explicit protocols for generating such all-photonic quantum-repeater states on-demand were put forward recently [11] where only two coupled quantum emitters are required. Such approaches exploit the strengths of the solid-state quantum photonics platform ideally, since only few matter qubits are required that rapidly can emit dozens of high-quality photonic qubits before the system decoheres. Alternative quantum-repeater architectures can be pursued if the solid-state quantum emitter is efficiently coupled to a long-lived quantum memory, such as nuclear spins [12].

Quantum communication relies on optical photons to distribute quantum information over long distances through optical fibers. The efficient interface to matter qubits allows generating advanced multi-photon entanglement sources. They may be exploited for real-word quantum-information processing applications by constructing architectures that only requires few matter qubits and potentially many photonic qubits. Solid-state quantum photonics systems can be tailored to these applications since the high cooperativity implies that each emitter can generate many photons. The ultimate dream of 'a quantum internet' [13] where quantum information is distributed in a fully secure manner over global distances may have come a step closer.

[1] I. Aharonovich, D. Englund, and M. Toth, Nat. Phot. **10**, 631 (2016).
[2] P. Lodahl, S. Mahmoodian, S. Stobbe, Rev. of Mod. Phys. **87**, 347 (2015).
[3] R.E. Evans et al., Science xxx (2018)
[4] A. Sipahigil et al., Science **354**, 847 (2016).
[5] L.-M. Duan and H.J. Kimble, Phys. Rev. Lett. **92**, 127902 (2004).
[6] N.H. Lindner and T. Rudolph, Phys. Rev. Lett. **103**, 113602 (2009).
[7] R.J. Warburton, Nat. Mater. **12**, 483 (2013).
[8] S.E. Economou, N. Lindner, and T. Rudolph, Phys. Rev. Lett. **105**, 093601 (2010).
[9] R. Raussendorf and H.J. Briegel, Phys. Rev. Lett. **86**, 5188 (2001).
[10] K. Azuma et al., Nat. Commun. **6**, 6787 (2015).
[11] D. Buterakos et al., Phys. Rev. X **7**, 041023 (2017).
[12] N. Kalb et al., Science **356**, 928 (2017).
[13] H.J. Kimble, Nature **453**, 1023 (2008).