Cavity-enhanced quantum network nodes

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A future quantum network will consist of quantum processors that are connected by quantum channels, just like conventional computers are wired up to form the Internet. In contrast to classical devices, however, the entanglement and non-local correlations available in a quantum-controlled system facilitate novel fundamental tests of quantum theory. In addition, they enable numerous applications in distributed quantum information processing, quantum communication, and precision measurement.

While pioneering experiments have demonstrated the entanglement of two quantum nodes separated by up to 1.3 km, and three nodes in the same laboratory, accessing the full potential of quantum networks requires scaling of these prototypes to many more nodes and global distances. This is an outstanding challenge, posing high demands on qubit control fidelity, qubit coherence time, and coupling efficiency between stationary and flying qubits.

In this work, I will describe how optical resonators facilitate quantum network nodes that achieve the above-mentioned prerequisites in different physical systems — trapped atoms, defect centers in wide-bandgap semiconductors, and rare-earth dopants — by enabling high-fidelity qubit initialization and readout, efficient generation of qubit-photon and remote qubit-qubit entanglement, as well as quantum gates between stationary and flying qubits. These advances open a realistic perspective towards the implementation of global-scale quantum networks in the near future.

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I. INTRODUCTION

The field of quantum technology aims at harnessing the strangeness and the power of quantum mechanics in order to implement devices that provide functionalities which are unattainable for any classical machine. In the last decades, four main fields of applications have been identified: First, quantum communication (Ekert and Renner 2014; Gisin and Thew 2007), which e.g. allows for provably secure encryption and authentication without any assumptions about the capabilities of an adversary. Second, quantum computation (Preskill 2018), which can fundamentally increase the size or speed upon solving specific computational tasks. Third, quantum simulation (Georgescu et al. 2014), in which complex and inaccessible quantum systems are emulated on a device that is more accessible, with the aim to gain a better understanding and to eventually guide the development of e.g. new materials and drugs. Finally, quantum sensing (Degen et al. 2017) that can improve the resolution or sensitivity of measurements.

The above applications have vastly different requirements with respect to the isolation, coherence and techniques to control the used quantum system. Therefore, often specialized hardware is employed. As an example, optical photons facilitate the distribution of quantum states at the fastest possible speed – the speed of light. Furthermore, they can be coupled into optical fibers and
FIG. 1 Quantum network and quantum repeater scheme. (a) In a quantum network, qubits at stationary nodes (black) are connected by photons that travel along optical channels (red/grey). Photon loss limits the distance of direct links to \(\sim 100\text{km}\). (b) This limit can be overcome in a network architecture with memory and communication qubits. To this end, each node is equipped with several qubits (filled circles). A subset, called ‘communication’ qubits (top), couples to the optical channels for probabilistic entanglement generation (dashed symbol) between remote nodes. A herald unambiguously tells when an entanglement attempt was successful (solid symbol). In this case, local two-qubit operations are used to swap the state of the communication qubits to the ‘memory’ qubits (bottom), which are isolated from the optical channels. (c) When memory qubits in neighboring segments have been entangled using a repeat-until-success strategy, local deterministic operations at the intermediate node can generate a maximally entangled cluster state of many qubits across the network. (d) A suited measurement of the inner qubits (arrows) can remove them from the cluster, generating an entangled state of memory qubits at the outer nodes even if their separation is too large for a direct photonic connection. Arbitrarily increasing the number or distance of entangled qubits is hampered by the loss of fidelity, which is exponential in the number of imperfect operations. To overcome this, new entanglement can be generated using the communication qubits (dashed), which may be then used to implement an error-correction layer, e.g. in the form of entanglement distillation (not shown).

transmitted with negligible decoherence over many kilo-

centers before they get absorbed. Finally, since photons do not interact, they can be multiplexed to the same channel to achieve higher rates. The above-mentioned properties make photons ideally suited for quantum communication (Ekert and Renner, 2014; Gisin and Thew, 2007), but are a severe disadvantage for all applications that require to keep quantum information over longer times, or to interact with other qubits or fields. This includes sensors of stationary fields (Degew et al., 2017), as well as processors and memory elements of a quantum computer (Preskill, 2018). Therefore, for the latter tasks other physical systems seem favorable. Most prominently, the spin of atoms in vacuum, or impurities and dopants in certain solids, offers unrivaled coherence time. Unfortunately, the isolation required for such long-term memory impedes the efficient and controlled coupling between qubits, as required for information processing.

In a hybrid system of light and matter qubits, forming a quantum network (Duan and Monroe, 2010; Reiser and Rempe, 2015) or "quantum internet" (Kimble, 2008; Wehner et al., 2018), one can achieve the above-mentioned contradicting requirements of implementing a controlled coupling between qubits while isolating them from the environment. The realization of such a quantum network may thus be an enabling technology for applications in all fields of quantum science: In quantum communication, entanglement-assisted communication can ensure unbreakable encryption (Ekert and Renner, 2014) and facilitate other important tasks such as authentication, position verification, secret sharing, voting, and compression (Buhrman et al., 2010; Wehner et al., 2018). In addition, a network of distributed quantum sensors may measure time (Komar et al., 2014), magnetic fields, gravity, or starlight (Gottesman et al., 2012; Khabiboulline et al., 2019) with unprecedented sensitivity or resolution (Proctor et al., 2018). Furthermore, in quantum computing and simulation a modular architecture may improve scalability (Awschalom et al., 2013; Kinos et al., 2021; Monroe and Kim, 2013) by connecting smaller processing units via photons. In such remote systems, one can avoid crosstalk and correlated errors that can be difficult to correct (Lidar and Brun, 2013). Finally, quantum networks may allow users with finite quantum capabilities to perform computations on a remote quantum supercomputer (Barz et al., 2012; Fitzsimons, 2017).

In addition to the known applications, novel possibilities of unforeseeable impact may emerge once global quantum networks become available. This puts the realization of a scalable quantum network at the forefront of today’s quantum science.

In this context, scalability means that adding another entangled node or increasing the distance between the nodes will add technical complexity and require additional resources, but will not be hindered by fundamental restrictions. In current physical systems, however, there
exist two fundamental restrictions that have to be overcome: Absorption that is unavoidable in any quantum channel, and errors caused by decoherence and control imperfections.

The former is the major challenge for scaling to larger distances: Consider an optical fiber link between distant nodes, operating at a telecommunication wavelength where the loss is lowest (Lines, 1984), such that the probability of transmitting a photon decreases exponentially with distance by only 0.2 dB/km. Assuming that one can realize a source of single photons with unity efficiency and the highest imaginable repetition rate, say 1 THz, the success rate will drop from 7 GHz after 100 km to once every 164 years after 1000 km. Clearly, such low rates hinder quantum secure communication and the extension of quantum networks to global distances.

But not only the success rate, also the quality of entangled states decreases exponentially when increasing the distance or the number of entangled particles. The reason is that all operations required to control qubits – both locally and remote – suffer from decoherence and technical imperfections, which accumulate with increasing number of qubits and operations. Thus, the realization of large-scale quantum networks will require suited protocols that counteract the accumulation of such imperfections. Such protocols are often termed "quantum error correction" (Devitt et al., 2013). A first idea how the mentioned challenges can be overcome in order to scale quantum networks to global distances was developed in 1998 (Briegel et al., 1998) in the seminal quantum repeater protocol, whose basic idea is explained in Fig. 1. The proposed scheme involves the following key elements: First, probabilistic but heralded remote entanglement used in a repeat-until-success strategy; second, network nodes equipped with several multiplexed qubits, which can be individually controlled and coupled by deterministic operations; and third, a layer of quantum error correction, originally in the form of nested entanglement distillation (Bennett et al., 1996).

The requirement of two-way signaling in the original scheme can be overcome using quantum error correction (Devitt et al., 2013) instead of entanglement distillation. Then, even protocols without long-lived quantum memories can be envisioned (Munro et al., 2012), which may facilitate improved rates in certain parameter regimes, but require very high-quality operations and low optical loss (Muralidharan et al., 2016). In contrast, variants of the original scheme can be realized with experimental parameters that are accessible in the near term (Rozpedek et al., 2018). Still, achieving the required multiplexing capacity and satisfying the high demands on efficiency and fidelity of all operations is a formidable experimental challenge. In this work, I will first explain why the integration of qubits into optical resonators opens promising perspectives to this end. I will then summarize the state of the art in cavity-enhanced quantum network nodes in the most promising experimental platforms studied so far. Finally, I will give an outlook to the future prospects and challenges of these systems.

II. CAVITY-ENHANCED QUANTUM NETWORK NODES

The experimental realization of quantum networks requires stationary nodes with qubits that can be initialized, manipulated, entangled and read individually with high fidelity. As shown in Fig. 1, this allows for the implementation of repeater architectures (Briegel et al., 1998), in which the nodes hold two types of qubits: First, memory qubits that can store quantum states much longer than the time it takes to distribute entanglement over the network. To achieve this, the memory qubits should be decoupled from the optical channel, but exhibit a deterministic and controlled coupling mechanism to the second qubit type called communication qubits. The main purpose of the latter is in turn to provide an efficient and coherent interface to optical photons. A natural candidate for the communication qubits are single emitters, such as trapped ions (Duan and Monroe, 2010), neutral atoms (Reiserer and Rempe, 2015), quantum dots (Gao et al., 2015; Lodahl et al., 2015), molecules (Wang et al., 2019), and spin qubits in solid state host materials (Atatüre et al., 2018; Awschalom et al., 2018; Wolfowicz et al., 2021; Zhong and Goldner, 2019). Often modeled as two-level systems, such emitters naturally exhibit nonlinear couplings (Chang et al., 2014). This allows for deterministic two-qubit quantum gates within the nodes, which can be a paramount advantage compared to quantum networking protocols that only use quantum memories and linear optics, which will be discussed in Sec. II.E.3.

The intrinsic nonlinearity of single emitters comes at the price of a moderate coupling to the photonic channels.
In such a scenario, the physics of the coupled system is described by the Jaynes-Cummings Hamiltonian (Jaynes and Cummings, 1963), as detailed in many textbooks (Haroche and Raimond, 2013). The relevant figure of merit for the light-matter interaction and its dynamics is the cooperativity $C = g^2/(2\kappa\gamma)$ which is determined by three quantities: First, the coupling constant $g$. Second, the polarization decay rate of the emitter $\gamma = \gamma_0 + \gamma_1 + \gamma_d$, which stems from of its spontaneous decay on the cavity-coupled optical (at rate $2\gamma_0$) or other transitions ($2\gamma_1$), as well as its dephasing rate $\gamma_d$. Finally, the cavity field decay rate $\kappa$, which is the sum of the decay into free space $\kappa_{\text{loss}}$ and into a desired output mode $\kappa_{\text{out}}$, as shown schematically in Fig. 2. Note that other texts (e.g., (Janitz et al., 2020)) define the energy rather than the field decay rates, which gives factors of 2 in all equations.

Often, one further distinguishes two regimes: That of "strong coupling", where $g \gg \kappa,\gamma$ and coherent re-absorption of photons is possible, and the "fast-cavity" regime with $\kappa > g \gg \gamma$ and $C \gg 1$. In both regimes, one gains access to efficient or even deterministic qubit-photon interactions (Borregaard et al., 2019), an invaluable resource for quantum networking (Reiserer and Rempe, 2019) and repeaters of the first generation (Briegel et al., 1998), and an indispensable prerequisite for high-rate quantum networks based on one-way quantum repeaters (Muralidharan et al., 2016). The main advantages provided by optical resonators will be described in the following sections: enhanced photon generation and absorption, improved spin-state initialization and readout, as well as spin-photon quantum gates.

A. Spin-photon entanglement generation

In many protocols, the first step to entangle remote quantum network nodes is to entangle the spin of the communication qubits with single photons or photonic cluster states that are then sent along the optical channel (Borregaard et al., 2019; Reiserer and Rempe, 2015). In free space, photon generation is typically realized by exciting the communication qubits with a short laser pulse, which is followed by spontaneous emission. If the emitter can decay via two transitions, the polarization of the photons can be entangled with the ground state spin level (Blinov et al., 2004), as shown in Fig. 3b. Alternatively, for emitters with only a single transition, entanglement

FIG. 3  Generation of spin photon entanglement. a) A single emitter is excited with a laser pulse (arrow). It decays back to the ground state while emitting a single photon (curly arrow), which is efficiently collected by the resonator. b) Level scheme with two optical transitions. After optical excitation (straight arrow), the emitter can decay to two different levels (A and B) by emitting light at different polarization or frequency. If the transitions have equal probability and are both supported by the cavity, a maximally entangled Bell state is generated. c) Protocol with a single optical transition. The qubit is prepared in a superposition between the two ground states (A and B). In a first step (left), the emitter is excited and emits a photon only if it is in state B. After swapping the ground-state populations, a second pulse excites the spin only if it is in A. For a balanced superposition, the scheme generates entanglement between the spin state and the emission time bin of a photonic qubit.

Consider a single two-level atom that interacts with a resonant single-photon light pulse in free space (Leuchs and Sondermann, 2013). To achieve the best coupling, the light field would be focused to a diffraction-limited spot, of the order of $A = (\lambda/2)^2$, with $\lambda$ denoting the optical wavelength. To estimate the interaction probability, this has to be compared to the absorption cross section of the emitter, $\sigma_{\text{abs}} = 3\lambda^2/2\pi$. Albeit $A \simeq \sigma_{\text{abs}}$ in this idealized situation, the photon absorption or scattering probability is in practice limited to about 20% due to finite solid angle coverage, imperfect spatial, temporal, and polarization mode matching (Leuchs and Sondermann, 2013). Coupling to several levels, which is present and strong in most emitters under study, leads to a further reduction. Therefore, better confinement of the electromagnetic field of the photon in both space and time is desirable for efficient quantum network nodes. This can be achieved by tailored nanophotonic waveguides (Lodahl et al., 2015; Vetsch et al., 2010), or by embedding the emitter into an optical resonator, which is the focus of this work.
with the emission time-bin is achieved using a suited sequence of ground state spin manipulations (Barrett and Kok, 2005; Bernien et al., 2013) (see Fig. 3c). In both settings, the obtained fidelity often depends on the excitation pulse duration, as the emitter can already decay during the pulse (Fischer et al., 2017), thus projecting the state or leaving the intended initial state. While this limitation is reduced with short pulses, their use is often impeded by the requirement not to drive unwanted transitions to other excited state levels.

Similar to the free-space scenario, photon generation by excitation with a short resonant laser pulse can also be implemented when the emitter is placed in a resonator (see Fig. 3a). In case the emitter dephasing is not the dominant rate, which is the typical situation in quantum networking experiments, the dynamics of the decay will be strongly modified: As the density of photonic modes is changed by the resonator, one can obtain an increased (Purcell, 1946) or decreased (Kleppner, 1981) radiative decay rate (Haroche and Raimond, 2013):

\[ \gamma_c = \frac{g^2 \kappa}{\kappa^2 + \Delta^2} \]  

As one can see, the decay into the resonator \( \gamma_c \) is suppressed when \( \Delta \), the detuning between emitter and cavity mode, is increased. On resonance, one finds that the decay rate is enhanced by the Purcell effect (Purcell, 1946) \( \gamma_c = P \gamma_0 \), where the Purcell factor \( P \) is related to the cooperativity via:

\[ P = 2C \frac{\gamma}{\gamma_0}. \]  

In the limit of large Purcell factor, \( \gamma_c \gg \gamma_0 + \gamma_1 \), such that the radiative decay of the emitter into the resonator is much faster than its decay into free-space modes. This has several beneficial effects in the context of quantum networks: First, when the resonator is overcoupled, i.e. the cavity field decay \( \kappa \) is dominated by the coupling into a single propagating mode \( \kappa_{\text{out}} \), one can strongly improve the photon collection probability and thus the efficiency of spin-photon entanglement generation. Second, one can enhance the photon generation rate, which is particularly relevant for emitters with slow radiative decay. But also for emitters that exhibit fast dephasing or considerable spectral diffusion, the increased decay rate can dramatically improve the coherence and spectral purity that is required for remote entanglement. A third advantage of the resonator is that it may enhance the emission into one out of several optical transitions, e.g. into a desired atomic ground state (see Sec. [III.B.1]) or crystal field level (Liu and Jacquie, 2005) (see Sec. [II.B.3]). Similarly, some emitters (see Sec. [III.B.2]) exhibit an undesired co-emission of photons whose contribution can be suppressed by the cavity-enhanced decay. Finally, the presence of a resonator enables efficient photon generation and photon absorption via off-resonant Raman transitions, which is detailed in the following.

### B. Stimulated Raman transitions

The above-mentioned scheme of photon generation by fast resonant excitation of a two-level system is applicable to any quantum emitter, but has intrinsic limitations to the spin-photon entanglement fidelity caused by the mentioned emission during the pulse (Fischer et al., 2017). In addition, the laser pulse has to be well-separated from the single-photon pulses by spatial (Bochmann et al., 2008), temporal or polarization filtering (Bernien et al., 2013). To improve the fidelity, one can use emitters with another ground-state level in a lambda configuration (Wilk et al., 2010). Here, scattered pump light can be filtered spectrally (Sipahigil et al., 2016), and the photon emission frequency can be widely tuned (Mücke et al., 2013; Sipahigil et al., 2016). In addition, re-excitation of the emitter is avoided when the ground-state level spacing is sufficient, enabling spin-photon entanglement with high fidelity (e.g. \( \gtrsim 99 \% \) at \( \sim 30 \% \) success probability) (Ritter et al., 2012), even beyond typical error correction fidelity thresholds in topological quantum computing (Fowler et al., 2012; Nickerson et al., 2013).

When the emitter is placed in a cavity, spectral filtering is intrinsically implemented by the resonator. Even more important, photon generation is made efficient and reversible (Cirac et al., 1997) when using a scheme called vacuum-stimulated Raman adiabatic passage, pioneered with trapped atoms (Kuhn et al., 1999) and later adapted to cavity-coupled solid-state emitters (Sun et al., 2018). The scheme can be implemented both in the Purcell and in the strong-coupling regime. To this end, the intensity of an external control laser is varied only on a slow time scale, such that the system is kept in a coherent Raman dark state. When the control is ramped up, exactly one photon is emitted from the resonator. The electromagnetic field mode of the photon is determined by the properties of the control laser pulse (Morin et al., 2019). Similarly, when the control field is ramped down, an impinging photon with matching temporal mode is absorbed (Boozer et al., 2007), and its polarization can be mapped to the spin state of the emitter (Specht et al., 2011), as shown in Fig. 4. This can be used to realize an efficient protocol for remote entanglement (Ritter et al., 2012). As the original atomic state is depleted, the scheme can be combined with state detection (detailed below) to herald successful entanglement attempts over a lossy channel.
C. Spin initialization and readout

A key capacity for the processing of quantum information is the ability to perform a faithful projective measurement of the qubit state. Ideally, this readout procedure is robust and fast enough to allow for feedback onto the quantum state, which is a prerequisite for measurement-based quantum information processing (Briegel et al., 2009), entanglement distillation (Bennett et al., 1996; Kalb et al., 2017), and quantum error correction in the network (Nickerson et al., 2013).

With emitters in free space, the quantum state is typically measured via photon scattering on a closed transition (Leibfried et al., 2003). High readout fidelity is achieved when at least one scattered photon is detected before the spin decays to other levels via unwanted optical transitions or other decay mechanisms. This requires, first, frequency selective excitation of only one qubit state; second, a fast cycling transition that decays predominantly back to the original state; and third, highly efficient detectors and collection optics. Each of the above-mentioned criteria is improved when the emitter is placed in an overcoupled optical resonator that enhances the emission into a propagating light mode (Bochmann et al., 2010). When \( P \gg 1 \), single-shot readout can be achieved even with emitters that lack a closed transition (Kindem et al., 2020; Raha et al., 2020).

However, the resonator also facilitates a different detection method, as the cavity transmission and reflection properties are altered by the presence of an emitter in a coupled energy level (Boozer et al., 2007). If the emitter and resonator frequency are known and stable, and in a regime where \( C \gg 1 \), this allows for state detection without photon scattering (Volz et al., 2011), which again means that the procedure works reliably for emitters that lack a closed transition.

The described techniques leave the qubit in the measured quantum state, such that they can also be used for state initialization. However, often optical pumping is used to this end. Here, the idea is to repeatedly excite the emitter until it has decayed to the desired state, which should be the only level that is not pumped. The fidelity of the process depends on the ratio of the desired pumping rate versus that of off-resonant driving on unwanted transitions, and on the lifetime of the ground state. Again, a resonator can enhance this process by improving the frequency selectivity and speeding up the decay rate. Combining optical pumping with subsequent state detection may then provide an optimal initialization procedure in terms of speed and fidelity (Reiserer et al., 2013b).

D. Spin-photon quantum gates

The previous sections have described the generation and absorption of photons from a cavity-coupled emitter. But the resonator also enables another, deterministic interaction mechanism of coupled stationary qubits with impinging photons that are reflected from it (Borgregaard et al., 2019; Duan and Kimble, 2004; Hofmann et al., 2003). In particular, when \( C \gg 1 \), a spin-photon quantum gate can be realized without photon absorption or scattering. For an intuitive explanation of the mechanism, consider an emitter in a lossless, overcoupled cavity in the strong coupling regime, see Fig. 5. A resonant photon is reflected off the coupling mirror which has a small transmission. If there is no emitter in the resonator, or the emitter is in an uncoupled qubit state, the light field leaking out of the resonator interferes destructively with the direct reflection at the coupling mirror, which means that the photon experiences a phase shift of \( \pi \). If, however, a resonant emitter is present, the energy eigenstates of the coupled system are split (Reiserer and Rempe, 2015). Thus, an impinging photon will now be off-resonant, meaning that it cannot enter the resonator but is reflected off the coupling mirror without a phase shift.

In effect, the reflection process leads to a conditional phase shift of \( \pi \) between the emitter and the photon, i.e. a controlled-phase quantum gate. After first experiments with trapped atoms (Reiserer et al., 2014; 2013b; Tiecke et al., 2014; Volz et al., 2014), quantum gates based on this mechanism have also been realized with superconducting qubits (Kono et al., 2018), quantum dots (Sun et al., 2018), and spins in diamond (Nguyen et al., 2019). Remarkably, the fidelity of the scheme is robust to many experimental imperfections as long as the spatial mode and frequency of the photons match that of the emitter-cavity system. In particular, the magnitude of the phase shift does not depend on the precise emitter-cavity coupling strength and detuning, making the scheme well-suited for emitters with considerable spectral diffusion.
FIG. 5 Cavity-based quantum gates. Insets: Phase shift mechanism. A single photon (arrows) is reflected from a single-sided optical resonator that contains a single emitter. The transition between the emitter energy levels (left) \(|2\rangle\) and \(|3\rangle\) is on resonance with the cavity frequency. When the emitter is in an off-resonant state \(|1\rangle\), the light field enters the resonator before it is reflected, acquiring a phase shift of \(\pi\). In the resonant emitter state \(|2\rangle\), however, there is no phase shift of the combined emitter-photon state: a) In the strong-coupling regime the energy spectrum is split (dashed lines). Thus, the photon is reflected without entering the resonator, acquiring no phase shift. b) In the Purcell regime, the light field enters the cavity. It drives the emitter to the excited state from which it decays back into the cavity mode. In this process, both the emitter and the photon acquire a \(\pi\) phase shift, such that their difference is again zero. Main graphs: Calculated phase difference as a function of the photon detuning (in units of the cavity linewidth \(\kappa\)) for systems with \(C = 50\) in the strong coupling regime (panel a, \(g = \sqrt{10}\kappa > \kappa > \gamma = \kappa/10\)) and in the Purcell regime (panel b, \(\kappa > g = \kappa/\sqrt{10} > \gamma = \kappa/1000\)). On resonance, a coupled emitter (red / gray) leads to a phase shift of \(\pi\) with respect to the case of an empty cavity or an uncoupled emitter (blue / dark gray), almost independent of the emitter detuning (e.g. \(\Delta_e = 5\gamma\), dashed), but sensitive to the cavity detuning (e.g. \(\Delta_c = 0.5\kappa\), dotted). The bandwidth of faithful operation is determined by the slope of the curves in Fig. 5 in the strong coupling regime, it is set by the cavity decay \(\kappa\), whereas in the Purcell regime it depends on the enhanced emitter decay rate \(g^2/\kappa\) [Kalb et al., 2015].

For an ideal system, the scheme explained above is deterministic. In practice, the efficiency and fidelity can be reduced by imperfect optical mode matching, by cavity scattering loss, and by a finite cooperativity. The scaling with the latter has been the subject of several theoretical works that investigated entanglement generation or quantum gates based on cavity-induced phase shifts. Depending on the used protocol, one finds a scaling of the failure probability \(\propto 1/C\) [Sørensen and Mølmer, 2003] or \(\propto 1/C\) [Kastoryano et al., 2011]. Again, using the concept of heralding, one can achieve almost perfect fidelity as long as \(C > 1\), at the price of a success rate reduction that depends on \(C\) [Borregaard et al., 2015, 2019].

The first experiment that implemented the above gate mechanism with trapped atoms at \(C \approx 3\) generated entangled states with 81% fidelity [Reiserer et al., 2014], mainly limited by imperfect optical mode matching and single-qubit control. The current record has been achieved with the SiV center in diamond with \(C \approx 10^2\) and an entangled-state fidelity of 94%. While this number is encouraging for the implementation of quantum repeaters of the first generation [Briegel et al., 1998, Muralidharan et al., 2016], further improvements will be necessary for implementing one-way quantum repeaters that require much higher fidelity operations, e.g. 99.9% in [Borregaard et al., 2020]. Still, such schemes may eventually become feasible using cavity-coupled emitters with deterministic spin-photon coupling [Borregaard et al., 2019].

E. Remote entanglement protocols

As summarized in the above sections, optical resonators can be used to enhance the capabilities of quantum network nodes. In the following, I will describe the application of these techniques towards the generation of heralded entanglement between remote communication qubits, which is a key resource for quantum networks and required for first-generation quantum repeaters [Briegel et al., 1998, Muralidharan et al., 2016]. In this context, two major approaches can be discriminated: First, entanglement swapping by photonic Bell-state measurements, and second, entanglement transfer by heralded absorption, as sketched in Fig. 6.

1. Entanglement swapping

In the first approach, both quantum network nodes first generate spin-photon entanglement using the tech-
Protocols to generate remote entanglement. a) Entanglement swapping. First, an entangled spin-photon state is generated at both quantum network nodes. The photons impinge onto a setup that allows for a measurement of the photonic Bell state (BSM). b) Entanglement by heralded absorption. Spin-photon entanglement is generated at the left node. The photon is sent to the second node, where it is absorbed such that the encoded quantum state is transferred to the spin of the emitter. c) Linear optical Bell state measurement for polarization qubits. The photons impinge on a non-polarizing beam splitter (NPBS), followed by two polarizing beam splitters (PBS) with single photon detectors in their horizontal (H) and vertical (V) output ports. A coincidence detection in two of the output ports heralds a specific Bell state, $|\Psi^+\rangle$ or $|\Psi^-\rangle$, depending on which detectors fire (yellow). In the other Bell states, photons have the same polarization and thus leave the NPBS in the same output port. Therefore, coincidences with the same polarization indicate that the other photon properties were not identical (ni).

Techniques described in Sec. II.A and II.B. The two photons are then sent to a photonic Bell-state analyzer, which is typically realized by linear optical elements and single-photon detectors. Coincidence detection events then allow one to distinguish two out of four photonic Bell states (Calsamiglia and Lütkenhaus, 2001) which is sufficient for heralded remote entanglement via entanglement swapping (Zukowski et al., 1993). In principle, the intrinsic inefficiency can be avoided by photonic quantum gates that use deterministic schemes (Hacker et al., 2016; Stolz et al., 2021), but so far do not reach the robustness, simplicity and efficiency of linear optical setups.

The physical effect that enables the Bell-state measurement in the latter is two-photon quantum interference (Hong et al., 1987). Note, however, that also single-photon interference protocols have been proposed (Cabrillo et al., 1999), which may offer increased rates in a high-loss regime (Campbell and Benjamin, 2008), as successfully demonstrated in (Kalb et al., 2017). In all such protocols, the mechanism only works if the photons are indistinguishable in all degrees of freedom except the one that encodes the entanglement with the spin (Reiserer and Rempe, 2015). This enforces accurate control over the photon emission time, frequency, polarization, and wavepacket, which is difficult to achieve in practice, leading to a reduction in fidelity. Still, the latter may be improved at the price of a reduced success probability when the interference signal is recorded with high temporal resolution and only events that occur within a short arrival time difference are considered (Bernien et al., 2013; Nölleke et al., 2013). The above-mentioned approach also works in the absence of a cavity (Bernien et al., 2013; Moehringer et al., 2007), and reasonable efficiencies can be achieved in systems with strong optical transitions and optimized collection (Stephenson et al., 2020). Still, embedding the emitter into a resonator can improve the rate and fidelity by enhancing the photon emission and collection probability, as detailed in Sec. II.A.

2. Heralded absorption

A second approach to remote entanglement generation that is enabled or enhanced by optical resonators uses heralded photon absorption, which overcomes the efficiency limitation of photonic Bell state analyzers (Lütkenhaus et al., 1999) and can be more robust with re-
spect to experimental imperfections. The process starts by spin-photon entanglement at one node. At the other node, the state of the photonic qubit is then transferred to the spin, as shown in Fig. 4b. To allow for repeat-until-success entanglement, successful transfer has to be heralded.

Two options exist to achieve this task: First, the absorption process can be the time reversal of the photon emission when using stimulated Raman adiabatic passage (Cirac et al., 1997) with multi-level emitters. This protocol can achieve the highest success probability and fidelity reported so far (Ritter et al., 2012). To herald successful qubit transfer, one has to detect whether the emitter has remained in its initial state or not, which can be accomplished using the techniques described in Sec. II.C. Alternatively, the control laser field can be replaced by the vacuum field of a second resonator. Then, the detection of a scattered Raman photon signals qubit transfer to the spin (Brekenfeld et al., 2020).

The second method for heralded photon storage is based on the cavity-based spin-photon quantum gate mechanism described in Sec. II.D. The first realization used a combination of a gate operation with spin manipulations, photon detection, and active feedback (Kalb et al., 2015), but also a passive implementation has been demonstrated (Bechler et al., 2018). Recently, the former approach has been used to generate entangled states by implementing a quantum gate between remote emitters (Daiss et al., 2021), highlighting its potential for quantum networks.

3. Ensemble-based approaches

The previous sections have focused on single emitters as quantum network nodes. This has the advantage that the non-linearity of the emitters allows for deterministic qubit interactions within a node, which improves the efficiency of first-generation and enables second- and third-generation quantum repeaters (Muralidharan et al., 2016). However, using single emitters requires resonators of very high quality. This difficulty is avoided when using the collective enhancement of the light-matter interaction with ensembles of emitters (Hammerer et al., 2010). Also in this approach, the exponential loss in optical fibers can be overcome with suited quantum repeater schemes, the first of which is often called the “DLCZ protocol” (Duan et al., 2001). In this scheme, atomic ensembles serve as both photon sources and quantum memories. Entanglement between remote ensembles is achieved in a repeat-until-success strategy by interfering emitted photons on a beam splitter. This induces a measurement-based non-linearity, similar to that in related concepts for photonic quantum computing (Knill et al., 2001).

The main protocols and first experimental implementations of quantum networking with atomic ensembles have been summarized in (Sangouard et al., 2011). Early milestone experiments include the probabilistic entanglement (Choi et al., 2005) of up to four different ensembles (Choi et al., 2010) using atoms in vacuum. Later, also ensembles in solid-state platforms were employed to realize DLCZ-type photon sources (Kutluer et al., 2017; Laplante et al., 2017), and the scheme has even been applied to entangle vibrations of remote optomechanical resonators (Riedinger et al., 2018).

While the original DLCZ scheme uses ensembles both as quantum memory and entanglement source, the latter can also be implemented by other techniques, e.g. non-linear optics. As an example, sources based on spontaneous parametric downconversion (SPDC) (Zhang et al., 2021) can facilitate a speedup of the remote entanglement rate when they are combined with efficient and broadband quantum memories (Simon et al., 2007a). Such devices can be realized with ensembles of trapped atoms or dopants in certain host crystals (Afzelius et al., 2015; Lvoysky et al., 2009; Tittel et al., 2010) offering a large multiplexing capacity (Afzelius et al., 2015; Seri et al., 2017; Usmani et al., 2010) that can be utilized in tailored quantum repeater protocols (Sinclair et al., 2014) to facilitate high-rate remote entanglement. First experiments along these lines were the storage of entangled photons in two crystals (Clausen et al., 2011; Sglanayurek et al., 2011), also heralded after interfering photons at telecommunications wavelength (Lago-Rivera et al., 2021). Other recent advances include the combination of an atomic ensemble photon source with a crystal-based memory, (Maring et al., 2017), and the entanglement of trapped-atom ensembles over 50 km of fiber (Yu et al., 2020). The latter experiments used frequency conversion to the telecommunications frequency band, a prerequisite for entanglement over many kilometers of optical fibers.

While the above studies have been performed without optical resonators, their use can enhance the efficiency of both photon storage and -generation. When using an SPDC source, cavities can reduce the required optical driving power, give higher brightness of the source, improve the mode-matching to single-mode fiber, and facilitate spectral filtering, as summarized in (Slattery et al., 2019). But also when using emitter ensembles as photon source, their integration in optical resonators can lead to a high brightness (Thompson et al., 2006) and enable a high readout efficiency of a stored excitation (Simon et al., 2007c). Furthermore, cavities can enhance other entanglement generation protocols, such as rephased amplified spontaneous emission (Williamson and Longdell, 2014).

Also considering the storage of photons, cavities can boost the efficiency. The achievable enhancement can be understood semiclassically (Tanji-Suzuki et al., 2011) or treated in a quantum-mechanical framework (Afzelius and Simon, 2010; Gorshkov et al., 2007). Typical exper-
ments use atoms in vacuum (Tanji et al., 2009) or rare-earth-doped crystals (Jobez et al., 2014; Sabooni et al., 2013). Remarkably, the enhancement of the light-matter-interaction strength offered by a cavity facilitates efficient quantum memories with a compact footprint, even down to nanophotonic devices (Wallucks et al., 2020; Zhong et al., 2017). Furthermore, the use of optical resonators can suppress the noise in multiplexed quantum memories (Heller et al., 2020), enable couplings between different memory modes (Simon et al., 2007b), and realize additional functions such as light-pulse switching by stored photons (Chen et al., 2013) if $C > 1$.

A drawback of the ensemble-based schemes presented above is the absence of an intrinsic nonlinearity. Thus, both in DLCZ and SPDC-based approaches the photon sources have to operate at a low efficiency to avoid the simultaneous emission of uncorrelated photons. Experimental imperfections lead to a further reduction of the remote entanglement rate, hampering large-scale quantum networks. To overcome this difficulty, adding a non-linear processing capacity to resonator-enhanced ensembles seems attractive. The main approaches are based on the Coulomb interaction between trapped ions (Casabone et al., 2015; Lamata et al., 2011), and on Rydberg interactions in ensembles of neutral atoms. The latter facilitate interactions between photons (Firstenberg et al., 2013), and even photon-photon quantum gates in a free-space setting (Tiarks et al., 2019). Again, the use of optical resonators can dramatically enhance the efficiency of such approaches, with a recent experiment demonstrating $>40\%$ (Stolz et al., 2021).

### III. EXPERIMENTAL REALIZATIONS

#### A. Optical resonator designs

The previous sections have focused on the underlying concepts of cavity-enhanced quantum network nodes. In the following, the current state-of-the-art of experimental systems will be summarized. An optical resonator that allows for the implementation of an efficient quantum interface to single emitters should fulfill the following two conditions: $\kappa_{\text{res}} \gg \kappa_{\text{loss}}$ and $C \gg 1$. This indicates the requirement for resonators with small mode volume $V$ and large quality factor $Q$, as $C \propto Q/V$ (Janitz et al., 2020; Lodahl et al., 2015; Reiserer and Rempe, 2015). Several approaches exist towards realizing such a resonator (Vahala, 2003), the most prominent being Fabry-Perot, ring, and photonic crystal resonators, as shown in Fig. 7.

Fabry-Perot resonators consist of two curved mirrors at a short distance, as shown in Fig. 7. In order to achieve high quality factors, Bragg reflectors are used, which consist of dielectric layers with alternating refractive indices, often $\text{Ta}_2\text{O}_5$ and $\text{SiO}_2$ with $n \simeq 2.1$ and $1.4$, respectively. The reflectors have to be deposited on atomically flat substrates to avoid excess loss by scattering. Transmission and scattering losses both below 1 ppm per mirror can be achieved with commercially available superpolished mirrors (Rempe et al., 1992), which gives a finesse around $F = 2 \cdot 10^9$, and even higher $Q = n \cdot F$, where the mode number $n$ counts the half-waves in the resonant cavity. In typical experiments, cooperativities around 10 are achieved using this approach (Reiserer and Rempe, 2015). Alternatively, low-roughness depressions with smaller radius of curvature can be fabricated by etching (Wachter et al., 2019) or laser machining (Hunger et al., 2012), both enabling finesse values beyond $2 \cdot 10^9$ and small mode volumes approaching a single cubic wavelength (Najer et al., 2019).

Emitters can be integrated into the resonator either by trapping atoms in vacuum (Reiserer and Rempe, 2015), or by depositing a nanocrystal (Casabone et al., 2018; Kaupp et al., 2016) or a thin crystalline membrane (Bogdanovic et al., 2017; Janitz et al., 2015; Merkel et al., 2020; Riedel et al., 2017; Ulanowski et al., 2021) on one of the mirrors. Experimentally achieved cooperativities (Colombe et al., 2007) and Purcell factors (Merkel et al., 2020; Ulanowski et al., 2021) are of the order of $10^2$. Coupling to the resonator mode is achieved by free-space optics (with $>99\%$ efficiency) or by directly coupling to a single-mode fiber with $\sim 90\%$ efficiency (Gulati et al., 2017; Niemietz et al., 2021).

Compared to the other approaches described below, Fabry-Perot resonators have two major advantages: First, they can be stabilized and tuned over many free spectral ranges using piezoelectric positioners. Second, to first order, the cooperativity does not depend on the cavity length $L$, as $Q \propto L$ and $V \propto L$. Thus, without reduction of the cooperativity an emitter can be kept at a large distance from all interfaces, which avoids the undesired influence of surface charges and paramagnetic trap states on the emitter stability.

A second approach to implement resonators with large cooperativity uses ring resonators, as shown in Fig. 7, either based on a whispering-gallery mode in microtoroids (Aoki et al., 2006), microspheres (Shomroni et al., 2014), or bottle resonators (Pöllinger et al., 2009), or using nanophotonic waveguide ring or racetrack resonators (Bogaerts et al., 2012). Emitters in the mode can exhibit a chiral coupling to light, leading to new possibilities for spin-photon interfaces (Lodahl et al., 2017). Tuning is typically achieved by temperature (Aoki et al., 2006) or, with bottle resonators, mechanically (Pöllinger et al., 2009). Experimentally achieved cooperativities with atoms (Aoki et al., 2006; Bechler et al., 2018; Junge et al., 2013; Scheucher et al., 2016) and Purcell factors with defect centers (Faraon et al., 2011) are on the order of 10, and high coupling efficiency is obtained via tapered fibers.

The third approach for efficient light-matter coupling
FIG. 7  Types of optical resonators. (a) Top: Experimental realization of a cryogenic Fabry-Perot cavity. The separation of the two mirrors (at the center), < 0.1 mm, is controlled using a piezo tube (white ring) that presses against stiff titanium springs (gray), achieving length fluctuations ≲ 1 pm. The setup is mounted using soft polymer springs (dark, side of the assembly) that isolate it from environmental vibrations. From [Merkel 2021]. Bottom: Microscope image of a diamond membrane with dimensions 0.01 × 0.3 × 0.2 mm³, deposited on a Bragg reflector. Microwave striplines (dark gray) allow for the application of microwave pulses to emitters in the membrane. (b) Ring resonator in the form of a microtoroid that supports a whispering-gallery mode with high quality factor. The coupling to a close-by nanofiber can be adjusted via their distance. Bottom: Scanning electron microscope image of a resonator with a diameter of 120 µm. Adapted from [Vahala 2003]. (c) Photonic crystal resonator. Top: Schematic of the setup. Using a conically tapered fiber, photons are coupled to a nanophotonic waveguide feeding the resonator at its end. Individual emitters are integrated into the resonator material, as seen in its cross section (inset). From [Weiss et al. 2021]. Bottom: Scanning electron microscope image of a resonator, formed by a periodic arrangement of holes along a silicon waveguide with a separation of ∼ 0.3 µm.

is based on photonic crystal resonators [Asano and Noda 2018, Lodahl et al. 2015], as shown in Fig. 7. When coupled to single emitters, cooperativities approaching 10⁹ [Sanutpraphoot et al. 2020] and Purcell factors approaching 10⁴ [Dibos et al. 2018] have been reported. Optimized structures in silicon even enable Q > 10⁷ [Asano et al. 2017] at mode volumes around λ³. When using dielectric enhancement, the effective mode volume can be further reduced by three orders of magnitude [Hu et al. 2018] while maintaining high Q. To use such a structure for quantum network nodes, however, the communication qubits have to be placed in the dielectric material of the resonator, which limits the applicability of the approach to specific combinations of emitter and host. Furthermore, the close proximity of interfaces will likely degrade the coherence of the emitter in such setting. Finally, care has to be taken in the evaluation of the cooperativity, as the dipole approximation assumes that the electric field only changes on a scale that is comparable to the wavelength [Cohen-Tannoudji et al. 1989], which is not satisfied in structures with deeply subwavelength dielectric features.

Tuning of photonic crystal cavities has been demonstrated by many techniques, including gas condensation (in the case of cryogenic resonators) [Mosor et al. 2005], nanomechanical actuation [Chew et al. 2010], electro-optical shifting [Lu et al. 2012] and temperature [Tiecke et al. 2014]. To couple into the resonators, different techniques can be used. The highest efficiencies, 97 %, are achieved using an adiabatic transition of the guided mode of a tapered optical fiber to that of a high-index dielectric waveguide [Tiecke et al. 2015] feeding the cavity. Other approaches use cleaved or lensed fibers with mode converters at the chip edge or diffraction gratings at the chip center, with typical efficiencies of 50 % [Vivien and Pavesi 2013].

B. Experimental platforms

In the following section, the physical systems that are used as communication qubits are described. As mentioned, their main purpose is to provide an efficient interface to photons, which is achieved by a suited optical resonator. Ideally, the photon wavelength will fall in the so-called telecommunications window, between 1500 and 1600 nm, where the loss of germanium-doped silica optical fibers is minimal [Lines 1984], around 0.2 dB/km, see Fig. 8a. While optical fiber links with lower loss would be desirable for global networks, no such system has been demonstrated in spite of an intense search over several decades. Still, when using the existing infrastructure photonic qubits can be transmitted over many kilometers with negligible decoherence even at room temperature and with moderate loss, see Fig. 8b.

To couple to these photons, the most prominent physical systems explored so far are single atoms (green), impurities in diamond, silicon or silicon carbide (red), and rare-earth dopants (blue). Quantum dots with their wide
Fig. 8 **Loss in optical fibers.** a) Absorption coefficient (black solid) of ultrapure "dry" silica fiber caused by Rayleigh scattering and infrared absorption (black dashed lines). Only few emitters (defects in diamond [C] and other semiconductors [Si and SiC]; atoms in vacuum [Rb, Cs, Ca+; Yb+]; rare-earth dopants [Tm3+, Yb3+, Er3+]) fall in the low-loss telecommunications window between 1250 nm and 1650 nm. b) Transmission after 50 km of optical fiber. At visible wavelengths, losses seem prohibitive. In contrast, in the telecommunications window the 10% transmission may be sufficient for quantum networking at a reasonable rate.

1. **Atoms in vacuum**

Many pioneering experiments in the field of quantum networks have used atoms trapped in vacuum. Since the first generation of remote entanglement (Moehring et al. 2007), several other experiments have achieved this milestone (Daiss et al. 2021, Hofmann et al. 2015, Ritter et al. 2012, Stephenson et al. 2020). By integrating the atoms into optical resonators, high efficiencies and many advanced protocols have been realized (Reiserer and Rempe, 2015), including teleportation (Langenfeld et al. 2021b, Nölleke et al. 2013), quantum
memories with single (Brekenfeld et al. 2020) Kalb et al. 2015 Specht et al. 2011 and several (Casabone et al. 2015) Langenfeld et al. 2020) atoms, photon-mediated quantum gates (Daiss et al. 2021) Dordevic et al. 2021 Hacker et al. 2016 Reiserer et al. 2014 Tiecke et al. 2014, nondestructive photon (Distante et al. 2021) Reiserer et al. 2013b) and photonic qubit (Niemietz et al. 2021) detection, and basic quantum repeater nodes (Langenfeld et al. 2021a). These advances have established trapped atoms as one of the leading experimental platforms for quantum networks.

To use atoms in vacuum as stationary and efficient network nodes, they have to be localized to a subwavelength spot. To this end, typically tight trapping potentials with trap frequencies on the order of a few hundred kHz are employed. The atoms are then confined in the Lamb-Dicke regime (Leibfried et al. 2003), where the motional state of the atom only occasionally changes in absorption and emission events. Still, efficient laser re-cooling is possible by various techniques (Reiserer and Rempe 2015), leaving the atom in the ground state of the potential (Reiserer et al. 2013a).

To implement the required trap, two approaches can be followed: First, electrical trapping of charged atoms (Leibfried et al. 2003), and second, optical trapping in far-detuned laser fields (Grimm et al. 2000). Importantly, both traps can be integrated with optical resonators in order to enhance the efficiency of spin-photon interactions, as shown in Fig. 9. As several atoms can be loaded to the same trap, quantum network nodes with several qubits can be realized (Casabone et al. 2013 Neuzner et al. 2016). These qubits can be different atomic species to avoid cross-talk during optical addressing and control (Iliev et al. 2017).

When trapped in vacuum, atoms are well isolated both from the environment and from one another. Thus, they can exhibit very long coherence times. With neutral atoms in optical resonators, encoding the qubit in a magnetic-field insensitive state has enabled a spin-echo time exceeding 100 ms (Körber et al. 2018), which is already promising for extended quantum networks. Eventually, in deep optical dipole traps the coherence will be limited by scattering of trap photons and by the requirement to periodically recool the atoms. This is avoided in electrical traps, where sympathetic cooling has recently enabled coherence times on the scale of one hour for Yb⁺, still far from the fundamental limitations of background gas scattering and hyperfine lifetime (Wang et al. 2021).

Such long coherence times pose no restrictions to the fidelity of single- and two-qubit operations within a node. Also, most technical limitations can be avoided by careful experimental design, by advanced pulses and pulse sequences adapted from nuclear magnetic resonance (Vandersypen and Chuang 2005), and by optimal control theory (Werschnik and Gross 2007). In this way, very high fidelities – exceeding 99.99 % (in the absence of a resonator) (Ballance et al. 2016) – for the preparation of arbitrary single qubit states have been demonstrated. To this end, the atom is first initialized to a single state by optical pumping. Then, irradiation of electromagnetic fields at the frequency of the qubit transition can induce arbitrary rotations. The use of optical rather than microwave fields eases individual addressing of several qubits in the same trap. A more detailed description of the techniques for single-atom control is given e.g. in (Reiserer and Rempe 2015).

In addition to the high-fidelity initialization, also faithful readout of the atomic state can be achieved using...
fluorescence state detection both in free-space and in optical resonators. In the latter, as described in Sec. [1.C], also resonator transmission can be used to reduce or even avoid readout-induced heating by photon scattering (Volz et al., 2011).

The implementation of quantum repeaters with dedicated memory and communication qubits also requires to control several atoms (Casabone et al., 2015; Neuzner et al., 2016) with individual addressing (Langenfeld et al., 2020; 2021b) and local deterministic two-qubit operations. To date, high-fidelity gates based on the Coulomb interaction have been achieved even between ions of different species (Hughes et al., 2020; Negnevitsky et al., 2018), with fidelities of 99.8% in the absence of a resonator. For neutral atoms, gates can be implemented via photonic interactions (Welte et al., 2018), or via dipolar coupling in a highly excited Rydberg state (Saffman et al., 2010), enabling entanglement generation fidelities > 99% in the absence of a resonator (Madjarov et al., 2020). Finally, the realization of quantum networks requires entanglement between remote nodes with high success probability η and fidelity F. In free space, values of η = 2 · 10^{-3} and F = 94% have been demonstrated with trapped ions (Stephenson et al., 2020). Neutral atoms in optical resonators have achieved η = 2% and F = 85% based on a Raman absorption protocol (Ritter et al., 2012), and η = 0.6% and F = 79% based on a remote quantum gate protocol (Daiss et al., 2021). As no fundamental limitations have been identified in these experiments, it seems likely that these values can be further improved, either based on the previously used protocols or on novel approaches towards heralded qubit storage (Bechler et al., 2018; Brekenfeld et al., 2020). Eventually, exceeding the error correction threshold of surface codes (Fowler et al., 2012) in a networked topology (Nicherson et al., 2013) (F ≈ 90% for remote entanglement) seems feasible. In this context, the F = 98% achieved when post-selecting on correct atomic state initialization (Ritter et al., 2012) is encouraging. To summarize, trapped atoms are a leading platform for the implementation of quantum networks and repeaters. The next steps towards the latter will likely involve the development of systems with more individually controlled qubits per node (Casabone et al., 2015; Huel et al., 2015; Langenfeld et al., 2020; 2021b), potentially with dedicated communication and memory qubits. Compared to other platforms under study, the main advantage of atoms trapped in vacuum is their excellent isolation, which enables long coherence and operations with exceptional fidelity. However, this comes at the price of requiring ultra-high vacuum and advanced optical setups with precisely stabilized high-power lasers. Albeit such systems have been realized in many laboratories, the implementation of field-deployable quantum network nodes based on trapped atoms is an outstanding engineering challenge.

2. Defect centers in semiconductors

Because of the mentioned technical overhead required to trap and cool single atoms in vacuum, significant effort has been invested in the search for solid-state alternatives. The first such system that has received considerable attention is the nitrogen-vacancy (NV) center in diamond. Landmark experiments with this platform include the demonstration of spin-photon entanglement (Togan et al., 2010), remote entanglement (Bernien et al., 2013) over distances up to 1.3 km (Hensen et al., 2015), the unconditional teleportation of a quantum state (Pfaff et al., 2014), the distillation of entanglement between remote quantum network nodes (Kalb et al., 2017), the deterministic delivery of remote entanglement (Hughreys et al., 2018), and the realization of a three-node quantum network (Pompili et al., 2021).

These experiments have been facilitated by the remarkable coherence properties of NV center spins in diamond (Doherty et al., 2013) up to room temperature, which forms the basis for many applications in quantum sensing (Degen et al., 2017). When transferring qubits to the nuclear spin of close-by 13C atoms, coherence can even be preserved for seconds (Maurer et al., 2012). Unfortunately, the coupling to phonons prevents the use of NV centers for remote entanglement generation at room temperature, as it leads to fast mixing of the excited state spin (Doherty et al., 2013). Instead, cryogenic operation at a typical temperature of 4 K is required to this end.

At such temperature, the individual optical transitions of the NV center can be resolved (Batalov et al., 2009). Some of them preserve the spin state well (Tamarat et al., 2008) and can thus be used for single-shot readout with high fidelity, provided the photon collection efficiency is high. This has first been achieved (Robledo et al., 2011) by placing the NV center into a solid immersion lens (Hadden et al., 2010). In this way, total internal reflection in high-refractive index host materials is avoided. The solid immersion lens can be combined with antireflective coatings to enhance the collection efficiency towards the theoretical maximum of 50% when using a lens system with a high numerical aperture.

Efficient collection also helps to increase the rate of remote entanglement by two-photon interference (Bernien et al., 2012; Sipahigil et al., 2012), which typically starts with the generation of spin-photon entanglement at both remote nodes. While initial experiments used polarization qubits (Togan et al., 2010), an alternative scheme based on time-bin qubits (Barrett and Kok, 2005) turned out to be more robust (Bernien et al., 2013), as it comes naturally with the decoupling of magnetic dephasing.

To realize this scheme and prove entanglement by reading the spin state in different bases, ground state control needs to be implemented. Albeit all-optical control can also be used with defect qubits (Santori et al., 2006; Yale et al., 2013), providing minimal crosstalk in dense...
Quantum network node based on defect centers in diamond. a) Typical experimental setting. Light is confined along the direction of a waveguide with triangular cross-section using a periodic pattern of holes. Individual defect centers, here two SiV-centers, are generated at the field maximum by implantation and annealing. Light is coupled to the resonator via a tapered optical fiber attached to a tapered end of the waveguide (not shown). b) Scanning-electron-micrograph of a diamond resonator, fabricated by reactive ion etching. The cavity is tuned such that the probe laser beam is on resonance. At the transition frequencies of two coupled SiVs, the transmission is almost completely suppressed, testifying the good emitter-resonator coupling. c) Spectral signature of the SiV-resonator coupling. The cavity is tuned such that the probe laser beam is on resonance. At the transition frequencies of two coupled SiVs, the transmission is almost completely suppressed, testifying the good emitter-resonator coupling, which can be quantified from the broadening of the SiV transition linewidth $\Gamma$. Adapted from [Evans et al., 2018].

systems, experiments typically use microwave pulses for their ease of implementation. In the NV center, the combination of a small magnetic bias field with the zero-field splitting of the defect (Doherty et al., 2013) leads to transition frequencies around 3 GHz, which can be conveniently applied via close-by wires or microwave striplines. In this way, control fidelities around 99.9% are routinely achieved (Hensen et al., 2015). Such high pulse fidelities also allow for dynamical decoupling with many control pulses to extend the coherence time of the electronic spin beyond 1 s at cryogenic temperature.

This is possible even in samples with natural isotope abundance (Abobeih et al., 2018), where about 99% of the carbon atoms have no nuclear spin. The few remaining $^{13}$C spins in the proximity of the NV electronic spin can be used as an additional resource for quantum information processing. In particular, they can serve as quantum registers (Dutt et al., 2007; Neumann et al., 2010), potentially with error correction (Cramer et al., 2010; Waldherr et al., 2014), and as robust memory qubits in a quantum network node (Reiserer et al., 2016), as they are decoupled from the optical channels and only interact with adjacent spins. Thus, using tailored sequences, the nuclear spin state is preserved for thousands of entanglement attempts (Kalb et al., 2018). In combination with the recently demonstrated potential for minute-long natural dephasing times (Bartling et al., 2021), this makes nuclear spin registers a unique resource for quantum networks.

To harness the potential of nuclear spins, they have to be controlled with high fidelity via the hyperfine interaction with the electronic spin. Strongly coupled spins can be controlled via frequency-selective electromagnetic fields (Dutt et al., 2007; Jelezko et al., 2004), but quickly lose their coherence when the electronic spin undergoes a random flip during entanglement generation attempts (Bloek et al., 2015). Therefore, the control of spin registers with weaker coupling is preferable. This comes at the price of slower local operations, whose speed is, however, not limiting in typical long-distance experiments. The required universal control can be achieved with a sequence of microwave pulses (Taminiau et al., 2014), potentially in combination with radiofrequency pulses to enhance the number of controllable spins and further improve the control fidelity (Bradley et al., 2019).

The main challenge towards the use of the NV center in quantum network nodes is the inefficiency of its zero-phonon optical transition (Doherty et al., 2013). Although single-photon protocols can substantially improve the rate (Campbell and Benjamin, 2008; Kalb et al., 2017) and thus facilitate repeat-until-success entanglement (Humphreys et al., 2018), for large-distance experiments the achievable rates seem prohibitively low. Therefore, it would be desirable to enhance the emission into the zero phonon line via the Purcell effect. This has first been achieved in nanophotonic resonators (Faraon et al., 2011), but the spectral diffusion of the optical transition observed in these experiments has hindered remote entanglement.

The frequency instability is attributed to charge fluctuations. While the state of the NV center itself can be well controlled (Doi et al., 2014; Siyushev et al., 2013), the Stark effects induce large jumps of the optical transition frequency when changing the state of close-by charge traps. In pure bulk crystals, the effect is small enough to be compensated by feedback (Acosta et al., 2012; Robledo et al., 2011), but the proximity of charge traps at the interface impedes the use of nanostructured diamond resonators.

A possible solution is to integrate bulk crystals with embedded NVs into Fabry-Perot resonators with small mode volume and high finesse. Purcell enhancement has
also been demonstrated in such setting (Riedel et al., 2017). Still, in spite of recent progress (Casabone et al., 2021; Fontana et al., 2021), it has turned out difficult to achieve the required length stability of a cavity with transversal scanning ability when operating in closed-cycle cryogenic systems (Bogdanovic et al., 2017; Janitz et al., 2015) with their typically strong vibrations. Instead, positioning individual defects within a rigid tube resonator assembly, as demonstrated with rare-earth dopants (Merkel et al., 2020), may provide a viable solution.

An alternative to such efforts is to use different defects than the NV center. In particular, the absence of a linear Stark shift for defects with inversion symmetry (Macfarlane, 2007) is beneficial for quantum networks nodes. Pioneering work used the SiV center in diamond that has promising optical properties in the negatively charged state, which both show stable transition frequencies and a comparably large fraction of zero-phonon-line emission. Two-photon interference experiments have demonstrated good photon indistinguishability (Sipahigil et al., 2014), which formed the basis for spin-spin entanglement by detecting photons emitted into a waveguide (Sipahigil et al., 2016). Experiments with photonic crystal resonators, as shown in Fig. 10, have now paved the way towards entanglement and quantum networking experiments (Evans et al., 2018; Nguyen et al., 2019) based on the phase-shift mechanism presented in Sec. 5. Remarkably, memory-enhanced quantum communication (Bhaskar et al., 2020) and the entanglement of several frequency-multiplexed emitters in the same resonator (Levonian et al., 2021) have been demonstrated in this platform, demonstrating the key steps required for implementing a quantum repeater, c.f. Fig 1.

Still, a drawback of the negatively charged SiV center is that so far, sufficient coherence of the ground state has only been obtained at mK temperature (Becker et al., 2018; Jahneke et al., 2015; Sukachev et al., 2017). Therefore, other group-IV defects that may operate at higher temperature, such as the neutral SiV (Rose et al., 2018) and the SnV (Rugai et al., 2021; Trusheim et al., 2020) may be favorable to enhance the prospects towards up-scaling. In this respect, the difficulty to grow pure diamond samples on a wafer scale — albeit favorable for the jewelry industry — may be an obstacle unless hybrid integration is used (Wan et al., 2020). This challenge is less pronounced in other large-bandgap semiconductors, such as silicon carbide. Also in this material, a large number of defects with promising properties have been identified. A recent overview is given in (Atatüre et al., 2018; Wollowicz et al., 2021). In particular, silicon vacancy centers (Nagy et al., 2019; Riedel et al., 2012) have demonstrated the generation of indistinguishable photons (Morioka et al., 2020) with high efficiency (Babin et al., 2021; Lukin et al., 2020), making SiC a promising candidate for the scaling of quantum networks. Note, however, that most defects in SiC and diamond emit light at frequencies where the transmission of optical fibers is moderate, as shown in Fig. 8. Therefore, photon conversion to the telecom band will be required to bridge global distances. Still, there are several emitters in the O-band around 1300 nm in SiC (Wang et al., 2020b; Wollowicz et al., 2020) and silicon (Bergeron et al., 2020; Durand et al., 2021) that may be used over larger distances without wavelength conversion.

3. Rare-earth dopants

In spite of the well-developed quantum network nodes based on trapped atoms and defects in large-bandgap semiconductors, the search for qubit systems with improved properties has not come to an end. In recent years, a third promising platform has emerged in this context: Crystals with rare-earth dopants, typically in the triply ionized state. These emitters exhibit optical transitions between electronic states in the inner 4f shell (Thiel et al., 2011), which are surrounded by filled 5s and 5p shells. The electrons in these outer orbitals shield the electric field of neighboring atoms in the crystal to a remarkable degree. Thus, the crystal field can be treated as a small perturbation to the energy levels of the free ion (Liu and Jacquier, 2005), such that the optical transition frequencies are almost independent of the host crystal. Remarkably, for one of the rare-earth dopants, erbium, these transitions fall within the telecommunication windows around 1550 nm. This is not only the basis for erbium-doped fiber lasers and amplifiers that are widespread in classical networks, but also makes this emitter an interesting candidate for quantum networks. In this context, the coherence of the optical transitions is paramount. Because of the shielding effect, at cryogenic temperature the coupling to phonons plays a negligible role in most hosts, and optical coherence of several ms is obtained in some systems (Böttger et al., 2006) — the longest observed in any solid.

Decoherence rates can also be extremely low in the ground state, where the precise value depends on the dopant, host crystal, and magnetic field (Thiel et al., 2011). In some systems, spin lifetimes of several weeks are observed, which forms the basis for the realization of quantum memories with exceptional lifetime of several hours (Zhong et al., 2015). In this context, the ideal host crystal exhibits a high Debye temperature, has a large bandgap and a low impurity concentration, and is free of nuclear magnetic moments (Atatüre et al., 2018; Wollowicz et al., 2021; Zhong and Goldner, 2019). In addition, the dopants should be integrated at a well-defined lattice site without generating too much strain or fluctuating charge traps. Finally, the crystal field levels should be well-split, which reduces phononic relaxation at a given
A common host crystal that fulfills most of these requirements is yttrium orthosilicate (YSO). Other materials can also be favorably used depending on the application. In many hosts, the crystal field splittings are on the order of a few THz, such that only the lowest manifold is significantly populated at liquid helium temperature. Upon optical excitation and decay, higher lying crystal field levels can be populated, but they quickly relax to the ground state by phonon emission.

The rare-earth dopants can be further classified into Kramers (typically Ce, Nd, Er, Yb) and non-Kramers (Pr, Eu, Tm) ions with odd and even number of 4f electrons, respectively. The degeneracy of the spin degree of freedom of Kramers ions with their single unpaired electron is lifted in an external magnetic field. The electronic state can then be modeled as a two-level system, i.e. an ideal qubit, in both the ground and optically excited state manifold (Thiel et al. 2011). Because of the large angular momentum of electrons in the 4f shell, the effective g-factor can be very large. This not only makes Kramers ions well-suited for molecular magnets ( Coronado, 2020), but could also allow for sensitive magnetic field sensors, microwave quantum memories ( Probst et al. 2015) and microwave-to-optical transducers ( Bartholomew et al. 2020). However, the strong and anisotropic interactions between Kramers dopants pose a challenge in this respect, as they can limit the spin lifetime (Car et al. 2019) and coherence even when applying tailored dynamical decoupling sequences ( Merkel et al. 2021).

Thus, using the electronic spin of Kramers dopants in quantum network nodes only seems promising at ultralow concentrations ( Cova Fariña et al. 2021; Dantec et al. 2021). As an alternative, long-lived quantum states can be encoded in the nuclear rather than electronic spin of the dopant ( Kindem et al. 2020; Ortu et al. 2018; Rakonjac et al. 2020; Rančić et al. 2018; Ruskuc et al. 2022). To this end, the electronic spin of Kramers dopants can also be frozen to the ground state at low temperature (≤ 2 K) and large magnetic fields (≥ 3 T). In this way, second-long coherence has been obtained (Rančić et al. 2018), and further improvement is expected in other hosts or at lower temperature.

In non-Kramers systems with their quenched electronic magnetic moment, even longer coherence times have been achieved, with the current record of 6 h for the hyperfine states in Eu:YSO ( Zhong et al. 2015). As this host exhibits a large number of nuclear spins, achieving such long coherence relies on two effects: First, the direction and amplitude of an external magnetic field is tuned such that the hyperfine transition frequency is first-order insensitive to magnetic field fluctuations ( Langer et al. 2005), which is possible even at zero external field with Kramers dopants ( Kindem et al. 2020; Ortu et al. 2018; Rakonjac et al. 2020). Second, the dynamics of the nuclear spin bath is slowed down in the “frozen core” that is generated around a rare-earth impurity by its magnetic moment ( Geschwind, 1972). The detrimental effect of the remaining slow nuclear spin bath dynamics, and other effects such as temperature drifts, can be alleviated by dynamical decoupling ( Suter and Álvarez, 2016).

Using the above-mentioned techniques, exceptional coherence of both ground-state and optical transitions can be obtained, offering great promise for the implementation of quantum networks. There is only one major challenge in this respect: The protected intra-4f transitions of the rare earths have only weak dipole moments. In free space, they are forbidden by symmetry, and even in crystals the observed lifetimes are typically in the range of milliseconds. For this reason, early quantum network experiments with rare-earth dopants have used large ensembles, as discussed in Sec. II.E.3 This has allowed for the implementation of efficient and broadband quantum memories ( Afzelius et al. 2015; Lyovskiy et al. 2009) that can store entangled photons ( Clausen et al. 2011; Saglamyurek et al. 2011) and offer a large multiplexing capacity ( Afzelius et al. 2015; Tittel et al. 2010) that can be utilized in tailored quantum repeater protocols ( Sinclair et al. 2014).

Still, in spite of low count rates, also single dopants ( Kolesov et al. 2012; Utikal et al. 2014) and nuclear spins in their proximity ( Kornher et al. 2020) have been detected. To use such system for quantum networks, improving the spin readout and photon generation speed is highly desirable. This can be achieved by integrating the emitters into optical resonators. Recent experiments with nanophotonic structures have resolved single dopants ( Dibos et al. 2018; Xia et al. 2021; Zhong et al. 2018), implemented single-shot readout ( Kindem et al. 2020; Raha et al. 2020) and nuclear spin registers ( Ruskuc et al. 2022), and demonstrated frequency-domain multiplexing and simultaneous control of several dopants ( Chen et al. 2020; Ulanowski et al. 2021). In these experiments, Purcell enhancement factors between 100 and 1000 have been achieved, reducing the optical lifetime to a few µs. This is short compared to the time it takes to transmit photons to remote quantum network nodes, such that it will not limit the achievable rate in remote entanglement experiments. To implement this basic quantum network functionality, the transition frequency of the emitters has to be stable, which is difficult in nanostructures, as the proximity of charge traps at the interface can lead to considerable spectral diffusion linewidths. Using Er:YSO in close proximity to a nanophotonic silicon resonator, ~10 MHz have been measured ( Dibos et al. 2018). In sites that lack a linear Stark shift ( Macfarlane, 2007), narrower lines have been observed, e.g. ~1 MHz with Yb:YVO, which is close to the lifetime limit in this particular experiment ( Kindem et al. 2020).

Another approach to obtain large Purcell enhancement
is the integration of rare-earth dopants into Fabry-Perot resonators. In contrast to experiments with nanocrystals (Casabone et al., 2018, 2021), the use of polished crystalline membranes allows for considerable Purcell enhancement while preserving the optical coherence and spectral stability observed in bulk materials (Merkel et al., 2020). Recent progress in this setup is shown in Fig. 11-d (Ulanowski et al., 2021). When operating at a large detuning from the center of the inhomogeneous line, single erbium dopants are spectrally resolved, albeit \( \sim 10^7 \) dopants fall within the cavity mode, and \( \sim 10^4 \) within a diffraction limited volume. The observed Purcell enhancement reaches \( \sim 70 \)-fold, depending on the position of the dopants in the standing-wave cavity mode (panel b). The frequency of the individual peaks is stable over several hours (panel d), with an averaged FWHM of \(< 0.2 \text{MHz}\). These narrow lines allow for resolving and controlling around \( 10^3 \) dopants when fast resonator tuning (Casabone et al., 2021) is implemented.

The remaining broadening is explained by the coupling of the electronic spin to the nuclear spin bath (Merkel, 2021). Thus, a considerable improvement is expected when using the isotope \( ^{167}\text{Er} \) at a magnetic field insensitive point (Ortu et al., 2018; Rakonjac et al., 2020). Alternatively, different host materials that have only a small abundance of nuclear magnetic moments can be considered. Recently studied materials include TiO\(_2\) (Phenicie et al., 2019), calcium tungstate (Dantec et al., 2021), and crystalline silicon (Berkman et al., 2021; Gritsch et al., 2021; Weiss et al., 2021; Yin et al., 2013).
The latter seems particularly promising, as isotopically purified material can be epitaxially grown by chemical vapor deposition (CVD) on a wafer scale (Mazzocchi et al. 2019).

Recent experiments in CVD silicon with natural isotope abundance have revealed narrow inhomogeneous (< 1 GHz) and homogeneous (≤ 20 kHz) linewidths of erbium dopants in particular lattice sites (Gritsch et al. 2021) - at a par with established host materials such as YSO. Remarkably, because of its high refractive index (de Vries and Lagendijk 1998), the radiative lifetime in silicon can be almost 50 times shorter than in YSO, enhancing the expected rate in quantum network experiments. When integrating isotopically purified membranes into Fabry-Perot resonators, a large number of dopants with negligible spectral diffusion may be controlled. Combined with its emission at telecommunication frequency and the prospect for second-long ground-state coherence (Rančić et al. 2018), this makes such systems a promising platform for the implementation of global quantum networks and quantum repeaters.

IV. SUMMARY AND OUTLOOK

The integration of single emitters into low-loss optical resonators has unique potential for the realization of scalable quantum networks. First steps into this direction have been taken in several experimental platforms, which have demonstrated the successful initialization, control, readout and remote entanglement of spin qubits based on efficient spin-photon interfaces. Still, scaling the demonstrated elementary quantum links to a network with many nodes that are distributed over global distances poses a formidable challenge. While many concepts that allow for such networks have been developed (Muralidharan et al. 2016; Wehner et al. 2018), the experimental requirements of high efficiency and almost 100% fidelity are difficult to achieve in all investigated physical platforms, and will therefore require a considerable engineering effort. Still, even with present experimental imperfections, the realization of a prototype quantum repeater seems within reach (Rozpedek et al. 2018).

Using such systems outside of the lab, e.g. in a global communication scenario, will only be possible if the devices are robust and cost-effective. Thus, the integration of the presented quantum network nodes with on-chip photonics (Wang et al. 2020a) will likely receive growing attention. Then, based on the current optical fiber infrastructure, the maximum separation of quantum repeater nodes will have to be on the order of 100 km, a distance after which 99% of the photons have been lost. Covering continental distances with an equally spaced network of high-vacuum chambers or closed-cycle 4He cryostats at such spacing seems feasible. This would be sufficient to provide users that have limited quantum processing capacity, e.g. only photodetectors and phase or polarization modulators, access to quantum network resources. Bridging the gaps between continents, however, seems more difficult and may favor the use of quantum satellites (Yin et al. 2017) or drones (Liu et al. 2020) rather than fiber-based links.

Going beyond point-to-point connections to generate entangled states of many nodes will require the implementation of entanglement distillation or quantum error correction. In the latter, current topological codes allow for error probabilities of a few per cent (Fowler et al. 2012; Nickerson et al. 2013), but then require an impractical overhead. Therefore, increasing the fidelity of remote entanglement far beyond what is achieved in current experiments will be paramount. To this end, the spectral stability of the emitters and resonators will have to be improved, in particular for solid-state qubits. Alternatively, much larger Purcell enhancement may be targeted.

If successful, the implementation of large quantum networks will open the door for novel fundamental tests (Brunner et al. 2014; Pikovski et al. 2015) at the forefront of contemporary quantum science. In addition, they will enable numerous applications. In particular, the upscaling of quantum computers may be based on a modular architecture ( Awschalom et al. 2013; Kinos et al. 2021; Monroe and Kim 2013), similar to the distribution of information processing among different components in classical high-performance computers and data centers. To this end, boosting the rate of remote entanglement to approach that of local quantum gates is highly desirable. This will further stimulate the research into optimized materials systems and resonator-integrated qubit platforms in the coming decades.

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