SCIENCE CHINA
Information Sciences

August 2020, Vol. 63 180503:1–180503:12
https://doi.org/10.1007/s11432-020-2953-y

• REVIEW •
Special Focus on Quantum Information

Quantum network based on non-classical light

Xiaolong SU[1,2*], Meihong WANG[1,2], Zhihui YAN[1,2], Xiaojun JIA[1,2*],
Changde XIE[1,2] & Kunchi PENG[1,2]

[1]*State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan* 030006*, China;*
[2]*Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan* 030006*, China*

Received 5 May 2020/Accepted 13 June 2020/Published online 9 July 2020

Abstract Quantum network enables quantum communication among quantum nodes and provides advantages that are unavailable in any classical network. Based on rapidly developing science and technology in quantum communication, the studies on quantum network have also made important progresses recent years. In this study, we briefly review the experimental progresses in building quantum network based on optical field and discuss the challenges toward a quantum Internet.

Keywords quantum network, non-classical light, quantum entanglement, quantum communication, quantum teleportation

Citation Su X L, Wang M H, Yan Z H, et al. Quantum network based on non-classical light. Sci China Inf Sci, 2020, 63(8): 180503, https://doi.org/10.1007/s11432-020-2953-y

1 Introduction

Our world has been benefited profoundly from the present Internet. Besides the classical Internet, quantum Internet in future will provide unprecedented technologies and applications. It plays an important role in developing the distributed quantum computation [1–4] and quantum communication, such as quantum key distribution (QKD) [5–7], quantum secure direct communication (QSDC) [8–10] and quantum secret sharing (QSS) [11]. Based on the achievements in the point-to-point quantum communication, for example, long distance quantum teleportation over 100 km [12–14] and QKD [6], building a quantum Internet has attracted more and more attention [15–17].

Recently, Wehner et al. [17] proposed six stages of building a quantum Internet based on the function of the Internet, which includes trusted repeater networks, prepare and measure networks, entanglement distribution networks, quantum memory networks, fault-tolerant few qubit networks and quantum computing networks. Different applications can be achieved in each stage and the function of the Internet increases from the first stage to the sixth stage. Up to now, several QKD networks have been established [18–24], which belong to the trusted repeater networks, i.e., the first stage of quantum Internet. The investigation of the next five stages of quantum Internet is in progress and there are several challenges that need to be solved. The ultimate version of a quantum Internet will consist of quantum computers and enable access to quantum computers at different authorized quantum nodes.

The physical implementation of a quantum Internet requires exchange of information among different physical systems [15]. Light is a natural carrier for information in communication because of the speed of light and the mature fiber channels. Atomic ensembles and solid state system are able to be used

---

[*] Corresponding author (email: suxl@sxu.edu.cn, jiaxj@sxu.edu.cn)

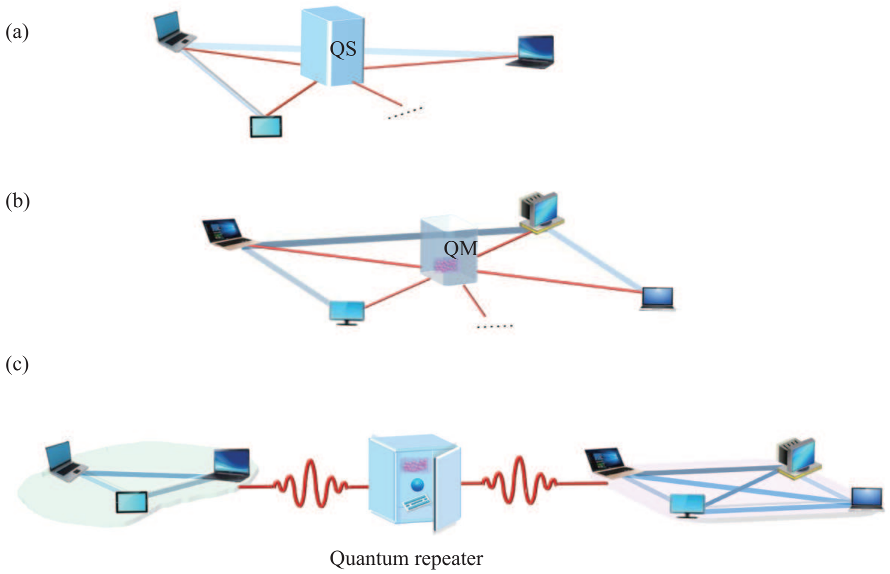

Figure 1 (Color online) Schematic of quantum networks. (a) Local all optical quantum network, which consists of a quantum server (QS) and several users; (b) local hybrid quantum network containing quantum memory (QM); (c) the schematic of quantum Internet consisting of a quantum repeater, which enables long distance quantum communication.

for quantum memory. Superconducting system and ion system have shown their power in quantum computation and can be applied in quantum servers. It is essential to connect these different systems and accomplish exchange of quantum information among them to build a quantum Internet. So, the final quantum Internet should be a hybrid quantum Internet involving a variety of physical systems.

Here, we review the progress of building quantum networks based on optical field, and discuss the challenges toward establishing a quantum Internet. The contents about local quantum networks, hybrid quantum networks and fully quantum Internet will be mentioned respectively.

2 The structure of quantum network

When we build a quantum network, it is essential to investigate the structure of it. For example, quantum state transmission in a butterfly network [25–27] and entanglement deployment in a quantum multi-hop network [28] have been investigated. According to the differences of transmission distances, quantum networks can be divided into local quantum networks and global quantum networks (quantum Internet), respectively. As shown in Figure 1(a), it is possible to establish a local all optical quantum network, which consists of only optical systems and usually is used to construct a metropolitan quantum network. A quantum server is utilized to prepare needed quantum states such as quantum entangled states and then the prepared quantum states are distributed to different quantum nodes. And then the quantum communication among quantum nodes, for example quantum communication based on quantum entanglement and QKD, can be implemented.

Besides, along with the development of technology of quantum memory, a local quantum network including a quantum memory unit will be available, as shown in Figure 1(b). The quantum memory unit involves some quantum systems other than optical systems, for example atomic [29–31] and solid state systems [32, 33], so such a quantum network would be a hybrid quantum network consisting of different quantum systems. By connecting space separated local quantum networks together, we will have a global quantum Internet, as shown in Figure 1(c). The connection can be completed by quantum channels or quantum repeaters [34, 35]. If the distance between two local networks are too far, quantum repeaters can be used to extend the transmission distance of quantum information.

3 All optical local quantum network

3.1 Quantum information with continuous variables

For quantum information based on optical systems, two different kinds of quantum variables are used, which are discrete variables and continuous variables, respectively. Discrete and continuous variables are quantum variables defined in finite and infinite Hilbert space, respectively. Optical quantum information with discrete variable (DV) and continuous variable (CV) systems are developing in parallel and have their own advantages and disadvantages respectively. DV system encodes information on discrete variables, such as polarization of photons. For the DV optical system, the maximal entanglement can be obtained but the generation of entanglement is probabilistic usually. While for the CV optical system, which encodes information on the amplitude and phase quadratures (corresponding to position and momentum respectively) of optical field, the generation of entanglement is deterministic but the perfect entanglement is not able to be obtained [36–38]. So far, tremendous progress has been achieved for optical quantum networks with DV and CV systems.

The amplitude and phase quadratures of an optical field $\hat{a}$ are defined as $\hat{x} = (\hat{a}+\hat{a}^\dagger)$ and $\hat{p} = (\hat{a}-\hat{a}^\dagger)/i$, respectively, where $\hat{a}$ and $\hat{a}^\dagger$ are annihilation and creation operators. In this definition, the variances of amplitude and phase quadratures of a vacuum state are normalized to $V(\hat{x}_0) = V(\hat{p}_0) = 1$, where the subscript 0 represents the vacuum state, which is named as the shot noise level (or quantum standard limit). CV quantum states frequently applied in quantum information include vacuum state, coherent state, squeezed state, and entangled state, which can be described in phase-space representation. These states belong to Gaussian state, whose characteristic function is in Gaussian distribution. By preparing Gaussian states, applying Gaussian unitaries on these states, and performing corresponding Gaussian measurements, the Gaussian quantum information can be implemented [37]. In the measurement of Gaussian states, homodyne and heterodyne detection systems are usually used. On the other hand, there are also CV quantum information based on non-Gaussian states, for example cat state, whose Wigner function is non-Gaussian.

Gaussian state can be completely characterized by the first and second statistical moments of quadratures of optical field, which are denoted by vector of first moments $\hat{\xi} = (\hat{x}_1, \hat{p}_1, \hat{x}_2, \hat{p}_2, \hat{x}_3, \hat{p}_3, \ldots, \hat{x}_N, \hat{p}_N)^{\mathrm{T}}$ and covariance matrix with elements $\sigma_{ij} = \frac{1}{2}\langle \hat{\xi}_i\hat{\xi}_j + \hat{\xi}_j\hat{\xi}_i\rangle - \langle\hat{\xi}_i\rangle\langle\hat{\xi}_j\rangle$, respectively. The covariance matrix of Einstein-Podolsky-Rosen (EPR) entangled state, which is a two-mode entangled state, is given by

$$\sigma_{AB} = \begin{pmatrix} V\boldsymbol{I} & \sqrt{V^2-1}\boldsymbol{Z} \\ \sqrt{V^2-1}\boldsymbol{Z} & V\boldsymbol{I} \end{pmatrix}, \tag{1}$$

where $V = \cosh 2r$ ($r \in [0, \infty)$ is the squeezing parameter), $\boldsymbol{I}$ and $\boldsymbol{Z}$ are the Pauli matrices

$$\boldsymbol{I} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \qquad \boldsymbol{Z} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \tag{2}$$

respectively.

CV multipartite entangled state, which is more complex than the two-mode EPR entangled state, is an important resource for quantum network. There are two kinds of well studied CV multipartite entangled states, which are Greenberger-Horne-Zeilinger (GHZ) state and cluster state, respectively. The CV GHZ state is an eigenstate with total momentum $\sum_j \hat{p}_j = 0$ (or position $\sum_j \hat{x}_j = 0$) and relative positions $\hat{x}_i - \hat{x}_j = 0$ (or momentums $\hat{p}_i - \hat{p}_j = 0$) ($i,\ j = 1, 2, \ldots, N$) [39], which has been applied in quantum teleportation network [40] and controlled dense coding [41]. The quadrature correlations (so-called nullifiers) of CV cluster state can be expressed by [42–44]

$$\left(\hat{p}_a - \sum_{b\in N_a} \hat{x}_b\right) \to 0, \qquad \forall a \in G. \tag{3}$$

The modes of $a \in G$ denote the vertices of the graph G, while the modes of $b \in N_a$ are the nearest neighbors of mode $\hat{a}$. For an ideal cluster state, the left-hand side of (3) tends to zero, so that the state is a simultaneous zero eigenstate of these quadrature combinations in the limit of infinite squeezing [42, 43].

3.2 Quantum key distribution network

QKD enables two authorized parties to share a secret key by transmitting quantum states through a quantum channel and followed by corresponding classical data processing. With the gradual maturation of QKD devices and technologies in recent years, the application of QKD is becoming more and more quickly. Based on extension of the point-to-point QKD protocol, several QKD networks have been proposed and demonstrated [18–24]. Especially, a QKD network more than 2000 km has been built among Beijing, Jinan, Hefei and Shanghai in China.

Recently, Diamanti et al. [6] reviewed practical challenges in QKD. DV QKD [5, 6] and CV QKD [37, 45–50] are developing in parallel. The security of the QKD system is limited by the imperfection of the devices [6], for example side-channel attacks [51–53]. One option to overcome this limitation is by using device-independent QKD protocol [54–56]. Since it is difficult to establish a device-independent QKD system, where the security of QKD relies on the violation of a Bell inequality, measurement-device-independent (MDI) QKD protocol [46, 47, 57–60], which removes the effect of measurement devices, has been proposed and demonstrated. Thus it will be more practical to build a MDI QKD network in future.

3.3 Entanglement distribution network

Entanglement is an important quantum resource in quantum information processing, such as quantum teleportation, quantum dense coding, quantum computation and quantum metrology. Distributing entanglement in a quantum network is a precondition for complete quantum communication and quantum computation based on entanglement. Multipartite entangled state can be used as a basic resource for building a local quantum network by distributing entangled photon qubits or optical modes to space separated quantum nodes. A convenient method to establish a local optical quantum network involving quantum entanglement is to distribute a multipartite entangled state among quantum nodes [39–41, 61], where the multipartite entangled state is prepared in a quantum server. Another method is to distribute several two-mode optical entangled states to different pairs of quantum nodes and then connect these quantum nodes together.

Usually quantum entanglement is distributed to quantum nodes directly, which is a traditional way. For example, the distributions of CV EPR entangled state over 20 km fiber [62] and CV quantum teleportation in 6 km fiber channel have been demonstrated [63], which make an essential step toward a real quantum network in fiber channel. It has also been shown that entanglement can be distributed by transmitting separable states in quantum channels [64, 65]. In this case, the state transmitted in quantum channel is not entangled, while entanglement is created after applying local operation and classical communications. Successively, this proposal has been demonstrated experimentally for distributing entanglement between two users [66–68]. It has been shown that under suitable conditions, distribution of entanglement via separable state has advantages in the presence of noise [69]. Recently, this method has been extended to distribute EPR steering [70], which is stronger than entanglement and has also been identified as a valuable resource for secure quantum information tasks.

For building a quantum Internet, a key procedure is to connect local quantum networks. In 2016, Pirandola and Braunstein [16] pointed out that one of the greatest challenges for implementing a globally distributed quantum computer or a quantum Internet is entangling quantum nodes across the network. It has been proposed that a global quantum Internet can be established by quantum entanglement swapping between space-separated local quantum networks [71, 72]. Quantum entanglement swapping, which makes two independent quantum entangled states without direct interaction become entangled, is an important technique in building quantum communication networks [73–80]. Quantum entanglement swapping is also known as quantum teleportation of one mode (a particle) of entangled states [78–81]. It was originally proposed and demonstrated in DV system [73, 74], and then was extended to CV system [77–80]. Recently,

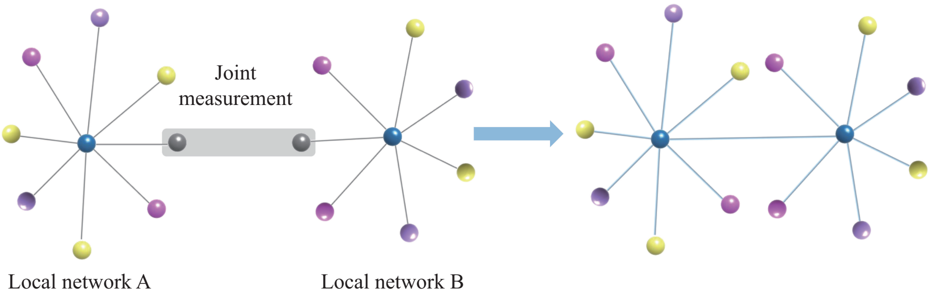

Figure 2 (Color online) Schematic of connecting two local quantum networks by quantum entanglement swapping. Two local quantum networks A and B are built by distributing two multipartite entangled states in several quantum nodes, respectively. By performing joint measurement on two optical modes coming from two local quantum networks and feedforward of measurement results to other quantum nodes, two quantum networks are emerged into one quantum network with new multipartite entangled states.

entanglement swapping between DV and CV systems has been demonstrated [82], which shows the power of hybrid quantum information processing [83].

The quantum entanglement swapping between two multipartite entangled states has been demonstrated experimentally [84], which shows the feasibility of connecting two local optical quantum networks by entanglement swapping. As shown in Figure 2, the entanglement swapping is implemented deterministically by means of a joint measurement on two optical modes coming from the two local networks respectively and the classical feedforward of the measurement results. After entanglement swapping, the two space-separated independent networks consisting of m and n quantum nodes respectively are merged into a larger network consisting of $m + n - 2$ quantum nodes, since two optical modes have been measured (see Figure 2), in which all unmeasured quantum modes in nodes are entangled and thus an Internet consisting of two local networks is built. In the experiment, two tripartite CV GHZ states are used to simulate two local quantum networks, respectively, and the dependence of the resultant entanglement on the transmission loss is investigated [84]. This technique is then extended to connect two CV cluster states, which can be used to build a quantum network based on CV cluster state [85]. It has also been shown that CV GHZ and cluster states can be used in measurement-device-independent quantum secret sharing and quantum conference network [86, 87], which provide concrete quantum communication schemes in CV quantum networks.

Besides quantum entanglement, quantum steering is another kind of quantum resource, which can be used to implement one-sided device independent QKD [88–92], secure quantum teleportation [93–95] and subchannel discrimination [96]. Comparing with quantum entanglement, the intrinsic character of quantum steering is that it is asymmetric, and thus it can be one-way [97–103]. Recently, experimental observation of multipartite EPR steering has been reported in optical networks [104] and photonic qubits [105, 106], respectively. In 2017, Deng et al. [107] experimentally demonstrated quantum steering in a four-mode Gaussian cluster state and verified the corresponding monogamy relations. In the same year, Qin et al. [108] realized the manipulation of the direction of Gaussian EPR steering in noisy environment. Wang et al. also proposed the swapping schemes for Gaussian EPR steering between two space-separated entangled states [109, 110], and presented EPR steering in a Gaussian weighted graph state [111], which can be used to construct a quantum network of quantum steering.

4 Hybrid quantum network containing quantum memory

Quantum memory is an essential building block for quantum repeater and quantum network. Various mechanisms of quantum memory have been developed, such as electromagnetically induced transparency (EIT) [29, 112–115], atomic Raman memory [30, 116, 117], gradient echo memory (GEM) [31, 118], and solid system [32, 33, 119–121]. Different methods of quantum memory have their own advantages and they are rapidly developing in recent years.

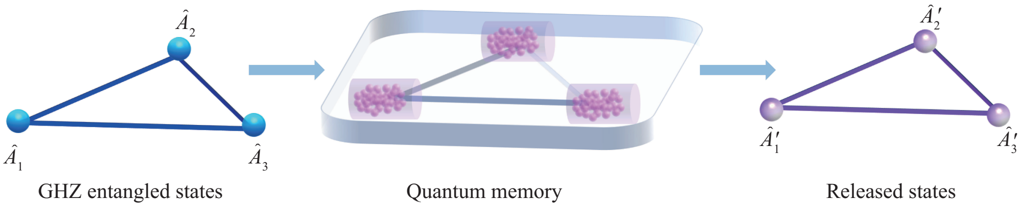

Figure 3 (Color online) Schematic of establishing quantum entanglement among three atomic ensembles. Quantum entanglement of three optical modes is transferred to three atomic ensembles.

In the following, we briefly introduce the progress of several typical quantum memory systems. In 2000, Fleischhauer et al. [112] reported that the optical pulses were effectively slowed down and trapped in the rubidium vapor by EIT process. In the experiment, one external field is used as the control field to make the opaque medium transparent. The other weak light, as the signal light, can propagate without dissipation and loss at a specific frequency and polarization, and the group speed of propagation is greatly reduced. Slow light is compressed greatly in space, and its signal pulse is almost completely stored in the atomic medium.

In 2013, Ding et al. [115] realized a true single-photon-carrying orbital angular momentum (OAM) stored in a cold atomic ensemble. In the same year, Xu et al. [122] presented a millisecond storage system based on EIT in which a moderate magnetic field is applied on a cold-atom cloud to lift Zeeman degeneracy, and thus the photonic polarization qubit states are stored as two magnetic-field-insensitive spin waves. Nicolas et al. [123] demonstrated the physical implementation of a quantum memory for OAM qubits. In 2018, Vernaz-Gris et al. [124] reported a quantum memory for polarization qubits that combines an average conditional fidelity above 99% and efficiency around 68%, thereby demonstrating a reversible qubit mapping where more information is retrieved than lost. Wang et al. [29] demonstrated a quantum memory for single-photon polarization qubits with an efficiency of $> 85\%$ and a fidelity of $> 99\%$ in 2019.

Since the bandwidth of quantum memory with EIT is limited, broad bandwidth atomic Raman memory has been developed [30, 116, 117]. A memory efficiency of above 82% and an unconditional fidelity up to 98% were obtained for the atomic Raman memory [30]. The GEM quantum memory provides an efficient method to store coherent optical pulse [31], and the maximum efficiency of 87% and the storage time of 1 ms have been achieved [118]. Besides quantum memory with atomic system, quantum memory with solid system is also in progress [32, 33, 119–121]. Comparing with the shorter storage time of atomic quantum memory, the storage time of solid state system can be up to six hours [120], and it can be used to store optical signals near to communication wavelength in fiber [119]. Recently, multiplexed storage and real-time manipulation based on a multiple degree-of-freedom quantum memory with solid state system have also been demonstrated [121].

Quantum memory of non-classical states is important for building a quantum network involving entanglement. In 2008, Honda et al. [125] and Appel et al. [126] realized the storage of the squeezed state, respectively. In 2010, Jensen et al. [113] demonstrated quantum memory for two-mode CV entangled states. In 2015, Ding et al. [117, 127] realized the quantum storage of OAM entanglement by using Raman mechanism. Recently, QSDC with single photons [9] and quantum memory [10] has been demonstrated experimentally.

In order to build a hybrid quantum network, it is essential to establish entanglement among quantum nodes containing quantum memory units. Yan et al. [128] demonstrated the establishment, storing and releasing of CV tripartite entanglement among three atomic ensembles, as shown in Figure 3. At first, a tripartite GHZ entangled state is prepared, and then the entanglement is transferred into three atomic ensembles located 2.6 m apart from each other via EIT interaction. After a given storage time, the preserved atomic entanglement is controllably released into three separated quantum channels. By measuring the entanglement of three output optical modes, the entanglement among three atomic ensembles is demonstrated. The method can be extended to establish entanglement among quantum nodes more than three by storing multipartite entangled states in quantum memory units.

5 Quantum Internet including quantum repeaters

Quantum repeater is an essential unit for long distance quantum communication and quantum networks, which was first proposed by Briegel et al. [34] to overcome the difficulty of the exponential fidelity decay of quantum entanglement in the channel. In 2001, Duan et al. [35] proposed a long-distance quantum communication scheme with atomic ensembles and linear optics, which allows to implement robust quantum communication over long lossy channels, which is known as Duan-Lukin-Cirac-Zoller (DLCZ) scheme. Yuan et al. [129] realized experimental demonstration of a quantum repeater node by entanglement swapping with storage and retrieval of light. Chen et al. [130] proposed and demonstrated a structure of nested purification experimentally, which can be applied in the implementation of a practical quantum repeater by combining with quantum memory. Kalb et al. [131] demonstrated entanglement distillation on an elementary quantum network consisting of a pair of two-qubit solid-state nodes separated by 2 m. Very recently, Bhaskar et al. [132] implemented asynchronous photonic Bell-state measurements by using a single solid-state spin memory integrated in a nanophotonnic diamond resonator, which represents a crucial step towards practical quantum repeaters and large-scale quantum networks. In 2020, Yu et al. [133] realized entanglement over 22 kilometers of field-deployed fibres via two-photon interference and entanglement over 50 kilometers of coiled fibres via single-photon interference.

Besides quantum repeater involving quantum memory, all optical quantum repeater is also developing [134–137]. In 2015, the concept of all-photonics quantum repeaters based on flying qubits was introduced by Azuma et al. [134], in which the quantum memories requirement is unnecessary. Buterakos et al. [135] presented a protocol for the deterministic generation of all-photonic quantum repeater from solid-state emitter. In 2019, Li et al. [136] performed an experimental demonstration of an all-photonic quantum repeater without quantum memory. In the experiment, by manipulating a 12-photon interferometer, a 2×2 parallel all-photonic quantum repeater is implemented, and an 89% enhancement of entanglement-generation rate over standard parallel entanglement swapping is observed. In the same year, time-reversed adaptive Bell measurement towards all-photonic quantum repeater has been reported in a proof-of-principle experiment by Hasegawa et al. [137].

6 Discussion and conclusion

The main challenge for practical applications of quantum information is how to build a quantum network in real world out of the lab. To do so, we have to construct local quantum networks firstly and to connect them through different channels, such as optical fiber [63,133] and free space channels [72,138]. Owing to that the present equipments for generating entanglement in the lab have not been integrated, thus, it is not convenient to be applied. It is necessary and significant to develop integrated quantum optical chips to replace the current bigger elements. We are pleased to see that the integrated quantum optical chips have had rapid progress recently [139–147]. Wang et al. [140] demonstrated a multidimensional integrated quantum photonic platform is able to generate, control, and analyze high-dimensional entanglement. Tang et al. [147] experimentally demonstrated quantum fast hitting by implementing two-dimensional quantum walks on graphs with up to 160 nodes and a depth of eight layers. Llewellyn et al. [143] demonstrated chip-to-chip quantum teleportation and multi-photon entanglement in silicon. Besides the rapid progress of DV integrated quantum optical chips, the CV chips are also developing [144–146].

In this manuscript, we briefly reviewed the progress of quantum networks based on non-classical light, which includes local all optical quantum networks, local hybrid quantum networks, and quantum Internet consisting of quantum repeater. Up to now, DV and CV quantum networks are developing in parallel. DV and CV quantum information systems have their own advantages and disadvantages, respectively. A hybrid quantum information processing [83], combining DV and CV units, will possibly overcome their disadvantages and bring us flush of hope to develop perfect quantum networks and Internet with powerful function better than any classical systems.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 11834010, 61925503, 61775127), Key Project of the National Key R&D program of China (Grant No. 2016YFA0301402), Applied Basic Research Program of Shanxi Province (Grant No. 201901D211164), and Fund for Shanxi "1331 Project" Key Subjects Construction.

References

1 Cirac J I, Ekert A K, Huelga S F, et al. Distributed quantum computation over noisy channels. Phys Rev A, 1999, 59: 4249–4254
2 Lim Y L, Beige A, Kwek L C. Repeat-until-success linear optics distributed quantum computing. Phys Rev Lett, 2005, 95: 030505
3 Jiang L, Taylor J M, Sørensen A S, et al. Distributed quantum computation based on small quantum registers. Phys Rev A, 2007, 76: 062323
4 Sheng Y B, Zhou L. Distributed secure quantum machine learning. Sci Bull, 2017, 62: 1025–1029
5 Gisin N, Ribordy G, Tittel W, et al. Quantum cryptography. Rev Mod Phys, 2002, 74: 145–195
6 Diamanti E, Lo H K, Qi B, et al. Practical challenges in quantum key distribution. npj Quantum Inf, 2016, 2: 16025
7 Huang A, Barz S, Andersson E, et al. Implementation vulnerabilities in general quantum cryptography. New J Phys, 2018, 20: 103016
8 Long G L, Liu X S. Theoretically efficient high-capacity quantum-key-distribution scheme. Phys Rev A, 2002, 65: 032302
9 Hu J Y, Yu B, Jing M Y, et al. Experimental quantum secure direct communication with single photons. Light Sci Appl, 2016, 5: e16144
10 Zhang W, Ding D S, Sheng Y B, et al. Quantum secure direct communication with quantum memory. Phys Rev Lett, 2017, 118: 220501
11 Hillery M, Bužek V, Berthiaume A. Quantum secret sharing. Phys Rev A, 1999, 59: 1829–1834
12 Yin J, Ren J G, Lu H, et al. Quantum teleportation and entanglement distribution over 100-kilometre free-space channels. Nature, 2012, 488: 185–188
13 Ma X S, Herbst T, Scheidl T, et al. Quantum teleportation over 143 kilometres using active feed-forward. Nature, 2012, 489: 269–273
14 Takesue H, Dyer S D, Stevens M J, et al. Quantum teleportation over 100 km of fiber using highly efficient superconducting nanowire single-photon detectors. Optica, 2015, 2: 832–835
15 Kimble H J. The quantum Internet. Nature, 2008, 453: 1023–1030
16 Pirandola S, Braunstein S L. Physics: unite to build a quantum Internet. Nature, 2016, 532: 169–171
17 Wehner S, Elkouss D, Hanson R. Quantum Internet: a vision for the road ahead. Science, 2018, 362: 303
18 Townsend P D. Quantum cryptography on multiuser optical fibre networks. Nature, 1997, 385: 47–49
19 Elliott C. The DARPA quantum network. In: Quantum Communications and Cryptography. Boca Raton: CRC Press, 2006
20 Poppe A, Peev M, Maurhart O. Outline of the SECOQC quantum-key-distribution network in vienna. Int J Quantum Inform, 2008, 6: 209–218
21 Wang S, Chen W, Yin Z Q, et al. Field test of wavelength-saving quantum key distribution network. Opt Lett, 2010, 35: 2454
22 Chen T Y, Wang J, Liang H, et al. Metropolitan all-pass and inter-city quantum communication network. Opt Express, 2010, 18: 27217–27225
23 Sasaki M, Fujiwara M, Ishizuka H, et al. Field test of quantum key distribution in the Tokyo QKD Network. Opt Express, 2011, 19: 10387–10409
24 Wang S, Chen W, Yin Z Q, et al. Field and long-term demonstration of a wide area quantum key distribution network. Opt Express, 2014, 22: 21739–21756
25 Yang Y, Yang J, Zhou Y, et al. Quantum network communication: a discrete-time quantum-walk approach. Sci China Inf Sci, 2018, 61: 042501
26 Li Z Z, Xu G, Chen X B, et al. Efficient quantum state transmission via perfect quantum network coding. Sci China Inf Sci, 2019, 62: 012501
27 Wang F, Luo M X, Xu G, et al. Photonic quantum network transmission assisted by the weak cross-Kerr nonlinearity. Sci China Phys Mech Astron, 2018, 61: 060312
28 Zou Z Z, Yu X T, Zhang Z C. Quantum connectivity optimization algorithms for entanglement source deployment in a quantum multi-hop network. Front Phys, 2018, 13: 130202
29 Wang Y, Li J, Zhang S, et al. Efficient quantum memory for single-photon polarization qubits. Nat Photon, 2019, 13: 346–351
30 Guo J, Feng X, Yang P, et al. High-performance Raman quantum memory with optimal control in room temperature atoms. Nat Commun, 2019, 10: 148
31 Hosseini M, Sparkes B M, Hétet G, et al. Coherent optical pulse sequencer for quantum applications. Nature, 2009, 461: 241–245
32 Hedges M P, Longdell J J, Li Y, et al. Efficient quantum memory for light. Nature, 2010, 465: 1052–1056
33 Clausen C, Usmani I, Bussiéres F, et al. Quantum storage of photonic entanglement in a crystal. Nature, 2011, 469: 508–511

34 Briegel H J, Dür W, Cirac J I, et al. Quantum repeaters: the role of imperfect local operations in quantum communication. Phys Rev Lett, 1998, 81: 5932–5935

35 Duan L M, Lukin M D, Cirac J I, et al. Long-distance quantum communication with atomic ensembles and linear optics. Nature, 2001, 414: 413–418

36 Braunstein S L, van Loock P. Quantum information with continuous variables. Rev Mod Phys, 2005, 77: 513–577

37 Weedbrook C, Pirandola S, García-Patrón R, et al. Gaussian quantum information. Rev Mod Phys, 2012, 84: 621–669

38 Wang X B, Hiroshima T, Tomita A, et al. Quantum information with Gaussian states. Phys Rep, 2007, 448: 1–111

39 van Loock P, Braunstein S L. Multipartite entanglement for continuous variables: a quantum teleportation network. Phys Rev Lett, 2000, 84: 3482–3485

40 Yonezawa H, Aoki T, Furusawa A. Demonstration of a quantum teleportation network for continuous variables. Nature, 2004, 431: 430–433

41 Jing J, Zhang J, Yan Y, et al. Experimental demonstration of tripartite entanglement and controlled dense coding for continuous variables. Phys Rev Lett, 2003, 90: 167903

42 Gu M, Weedbrook C, Menicucci N C, et al. Quantum computing with continuous-variable clusters. Phys Rev A, 2009, 79: 062318

43 Zhang J, Braunstein S L. Continuous-variable Gaussian analog of cluster states. Phys Rev A, 2006, 73: 032318

44 van Loock P, Weedbrook C, Gu M. Building Gaussian cluster states by linear optics. Phys Rev A, 2007, 76: 032321

45 Su X, Wang W, Wang Y, et al. Continuous variable quantum key distribution based on optical entangled states without signal modulation. EPL, 2009, 87: 20005

46 Li Z, Zhang Y C, Xu F, et al. Continuous-variable measurement-device-independent quantum key distribution. Phys Rev A, 2014, 89: 052301

47 Ma X C, Sun S H, Jiang M S, et al. Gaussian-modulated coherent-state measurement-device-independent quantum key distribution. Phys Rev A, 2014, 89: 042335

48 Wang N, Du S, Liu W, et al. Long-distance continuous-variable quantum key distribution with entangled states. Phys Rev Appl, 2018, 10: 064028

49 Chai G, Li D, Cao Z, et al. Blind channel estimation for continuous–variable quantum key distribution. Quantum Eng, 2020, 2: e37

50 He M, Malaney R, Green J. Multimode CV-QKD with non-Gaussian operations. Quantum Eng, 2020, 2: e40

51 Zhao Y, Fung C H F, Qi B, et al. Quantum hacking: experimental demonstration of time-shift attack against practical quantum-key-distribution systems. Phys Rev A, 2008, 78: 042333

52 Lydersen L, Wiechers C, Wittmann C, et al. Hacking commercial quantum cryptography systems by tailored bright illumination. Nat Photon, 2010, 4: 686–689

53 Xu F, Qi B, Lo H K. Experimental demonstration of phase-remapping attack in a practical quantum key distribution system. New J Phys, 2010, 12: 113026

54 Mayers D, Yao A. Quantum cryptography with imperfect apparatus. In: Proceedings of the 39th Annual Symposium on Foundations of Computer Science, 1998. 503–509

55 Acín A, Brunner N, Gisin N, et al. Device-independent security of quantum cryptography against collective attacks. Phys Rev Lett, 2007, 98: 230501

56 Braunstein S L, Pirandola S. Side-channel-free quantum key distribution. Phys Rev Lett, 2012, 108: 130502

57 Lo H K, Curty M, Qi B. Measurement-device-independent quantum key distribution. Phys Rev Lett, 2012, 108: 130503

58 Yin H L, Chen T Y, Yu Z W, et al. Measurement-device-independent quantum key distribution over a 404 km optical fiber. Phys Rev Lett, 2016, 117: 190501

59 Liu H, Wang W, Wei K, et al. Experimental demonstration of high-rate measurement-device-independent quantum key distribution over asymmetric channels. Phys Rev Lett, 2019, 122: 160501

60 Cui Z X, Zhong W, Zhou L, et al. Measurement-device-independent quantum key distribution with hyper-encoding. Sci China Phys Mech Astron, 2019, 62: 110311

61 Roslund J, de Araújo R M, Jiang S, et al. Wavelength-multiplexed quantum networks with ultrafast frequency combs. Nat Photon, 2014, 8: 109–112

62 Feng J, Wan Z, Li Y, et al. Distribution of continuous variable quantum entanglement at a telecommunication wavelength over 20 km of optical fiber. Opt Lett, 2017, 42: 3399

63 Huo M, Qin J, Cheng J, et al. Deterministic quantum teleportation through fiber channels. Sci Adv, 2018, 4: eaas9401

64 Cubitt T S, Verstraete F, Dür W, et al. Separable states can be used to distribute entanglement. Phys Rev Lett, 2003, 91: 037902

65 Mišta J L, Korolkova N. Improving continuous-variable entanglement distribution by separable states. Phys Rev A, 2009, 80: 032310

66 Fedrizzi A, Zuppardo M, Gillett G G, et al. Experimental distribution of entanglement with separable carriers. Phys Rev Lett, 2013, 111: 230504

67 Vollmer C E, Schulze D, Eberle T, et al. Experimental entanglement distribution by separable states. Phys Rev Lett, 2013, 111: 230505

68 Peuntinger C, Chille V, Mišta J L, et al. Distributing entanglement with separable states. Phys Rev Lett, 2013, 111: 230506

69 Zuppardo M, Krisnanda T, Paterek T, et al. Excessive distribution of quantum entanglement. Phys Rev A, 2016, 93: 012305

70 Xiang Y, Su X, Mišta J L, et al. Multipartite Einstein-Podolsky-Rosen steering sharing with separable states. Phys Rev A, 2019, 99: 010104

71 Jing J, Xie C, Peng K. Tripartite entanglement swapping of bright light beams. Nonlinear Opt Quantum Opt, 2003, 30: 89–102

72 Kómár P, Kessler E M, Bishof M, et al. A quantum network of clocks. Nat Phys, 2014, 10: 582–587

73 Żukowski M, Zeilinger A, Horne M A, et al. "Event-ready-detectors" Bell experiment via entanglement swapping. Phys Rev Lett, 1993, 71: 4287–4290

74 Pan J W, Bouwmeester D, Weinfurter H, et al. Experimental entanglement swapping: entangling photons that never interacted. Phys Rev Lett, 1998, 80: 3891–3894

75 Sciarrino F, Lombardi E, Milani G, et al. Delayed-choice entanglement swapping with vacuum-one-photon quantum states. Phys Rev A, 2002, 66: 024309

76 de Riedmatten H, Marcikic I, van Houwelingen J A W, et al. Long-distance entanglement swapping with photons from separated sources. Phys Rev A, 2005, 71: 050302

77 Tan S M. Confirming entanglement in continuous variable quantum teleportation. Phys Rev A, 1999, 60: 2752–2758

78 van Loock P, Braunstein S L. Unconditional teleportation of continuous-variable entanglement. Phys Rev A, 1999, 61: 010302

79 Jia X, Su X, Pan Q, et al. Experimental demonstration of unconditional entanglement swapping for continuous variables. Phys Rev Lett, 2004, 93: 250503

80 Takei N, Yonezawa H, Aoki T, et al. High-fidelity teleportation beyond the no-cloning limit and entanglement swapping for continuous variables. Phys Rev Lett, 2005, 94: 220502

81 Yang L, Liu Y C, Li Y S. Quantum teleportation of particles in an environment. Chin Phys B, 2020, 29: 060301

82 Takeda S, Fuwa M, van Loock P, et al. Entanglement swapping between discrete and continuous variables. Phys Rev Lett, 2015, 114: 100501

83 Andersen U L, Neergaard-Nielsen J S, van Loock P, et al. Hybrid discrete- and continuous-variable quantum information. Nat Phys, 2015, 11: 713–719

84 Su X, Tian C, Deng X, et al. Quantum entanglement swapping between two multipartite entangled states. Phys Rev Lett, 2016, 117: 240503

85 Tian C, Han D, Wang Y, et al. Connecting two Gaussian cluster states by quantum entanglement swapping. Opt Express, 2018, 26: 29159–29169

86 Wu Y, Zhou J, Gong X, et al. Continuous-variable measurement-device-independent multipartite quantum communication. Phys Rev A, 2016, 93: 022325

87 Wang Y, Tian C X, Su Q, et al. Measurement-device-independent quantum secret sharing and quantum conference based on Gaussian cluster state. Sci China Inf Sci, 2019, 62: 072501

88 Tomamichel M, Renner R. Uncertainty relation for smooth entropies. Phys Rev Lett, 2011, 106: 110506

89 Branciard C, Cavalcanti E G, Walborn S P, et al. One-sided device-independent quantum key distribution: security, feasibility, and the connection with steering. Phys Rev A, 2012, 85: 010301

90 Walk N, Hosseini S, Geng J, et al. Experimental demonstration of Gaussian protocols for one-sided device-independent quantum key distribution. Optica, 2016, 3: 634–642

91 Gehring T, Händchen V, Duhme J, et al. Implementation of continuous-variable quantum key distribution with composable and one-sided-device-independent security against coherent attacks. Nat Commun, 2015, 6: 8795

92 Gallego R, Aolita L. Resource theory of steering. Phys Rev X, 2015, 5: 041008

93 Reid M D. Signifying quantum benchmarks for qubit teleportation and secure quantum communication using Einstein-Podolsky-Rosen steering inequalities. Phys Rev A, 2013, 88: 062338

94 He Q, Rosales-Zárate L, Adesso G, et al. Secure continuous variable teleportation and Einstein-Podolsky-Rosen steering. Phys Rev Lett, 2015, 115: 180502

95 Chiu C Y, Lambert N, Liao T L, et al. No-cloning of quantum steering. npj Quantum Inf, 2016, 2: 16020

96 Piani M, Watrous J. Necessary and sufficient quantum information characterization of Einstein-Podolsky-Rosen steering. Phys Rev Lett, 2015, 114: 060404

97 Midgley S L W, Ferris A J, Olsen M K. Asymmetric Gaussian steering: when Alice and Bob disagree. Phys Rev A, 2010, 81: 022101

98 He Q Y, Gong Q H, Reid M D. Classifying directional Gaussian entanglement, Einstein-Podolsky-Rosen steering, and discord. Phys Rev Lett, 2015, 114: 060402

99 Kogias I, Lee A R, Ragy S, et al. Quantification of Gaussian quantum steering. Phys Rev Lett, 2015, 114: 060403

100 Rosales-Zárate L, Teh R Y, Kiesewetter S, et al. Decoherence of Einstein-Podolsky-Rosen steering. J Opt Soc Am B, 2015, 32: A82–A91

101 Händchen V, Eberle T, Steinlechner S, et al. Observation of one-way Einstein-Podolsky-Rosen steering. Nat Photon, 2012, 6: 596–599

102 Wollmann S, Walk N, Bennet A J, et al. Observation of genuine one-way Einstein-Podolsky-Rosen steering. Phys Rev Lett, 2016, 116: 160403

103 Sun K, Ye X J, Xu J S, et al. Experimental quantification of asymmetric Einstein-Podolsky-Rosen steering. Phys Rev Lett, 2016, 116: 160404

104 Armstrong S, Wang M, Teh R Y, et al. Multipartite Einstein-Podolsky-Rosen steering and genuine tripartite entan-

glement with optical networks. Nat Phys, 2015, 11: 167–172
105 Cavalcanti D, Skrzypczyk P, Aguilar G H, et al. Detection of entanglement in asymmetric quantum networks and multipartite quantum steering. Nat Commun, 2015, 6: 7941
106 Li C M, Chen K, Chen Y N, et al. Genuine high-order Einstein-Podolsky-Rosen steering. Phys Rev Lett, 2015, 115: 010402
107 Deng X, Xiang Y, Tian C, et al. Demonstration of monogamy relations for Einstein-Podolsky-Rosen steering in Gaussian cluster states. Phys Rev Lett, 2017, 118: 230501
108 Qin Z, Deng X, Tian C, et al. Manipulating the direction of Einstein-Podolsky-Rosen steering. Phys Rev A, 2017, 95: 052114
109 Wang M, Qin Z, Su X. Swapping of Gaussian Einstein-Podolsky-Rosen steering. Phys Rev A, 2017, 95: 052311
110 Wang M, Qin Z, Wang Y, et al. Einstein-Podolsky-Rosen-steering swapping between two Gaussian multipartite entangled states. Phys Rev A, 2017, 96: 022307
111 Wang M, Deng X, Qin Z, et al. Einstein-Podolsky-Rosen steering in Gaussian weighted graph states. Phys Rev A, 2019, 100: 022328
112 Fleischhauer M, Lukin M D. Dark-state polaritons in electromagnetically induced transparency. Phys Rev Lett, 2000, 84: 5094–5097
113 Jensen K, Wasilewski W, Krauter H, et al. Quantum memory for entangled continuous-variable states. Nat Phys, 2011, 7: 13–16
114 Zhang H, Jin X M, Yang J, et al. Preparation and storage of frequency-uncorrelated entangled photons from cavity-enhanced spontaneous parametric downconversion. Nat Photon, 2011, 5: 628–632
115 Ding D S, Zhou Z Y, Shi B S, et al. Single-photon-level quantum image memory based on cold atomic ensembles. Nat Commun, 2013, 4: 2527
116 Reim K F, Nunn J, Lorenz V O, et al. Towards high-speed optical quantum memories. Nat Photon, 2010, 4: 218–221
117 Ding D S, Zhang W, Zhou Z Y, et al. Raman quantum memory of photonic polarized entanglement. Nat Photon, 2015, 9: 332–338
118 Cho Y W, Campbell G T, Everett J L, et al. Highly efficient optical quantum memory with long coherence time in cold atoms. Optica, 2016, 3: 100
119 Saglamyurek E, Sinclair N, Jin J, et al. Broadband waveguide quantum memory for entangled photons. Nature, 2011, 469: 512–515
120 Zhong M, Hedges M P, Ahlefeldt R L, et al. Optically addressable nuclear spins in a solid with a six-hour coherence time. Nature, 2015, 517: 177–180
121 Yang T S, Zhou Z Q, Hua Y L, et al. Multiplexed storage and real-time manipulation based on a multiple degree-of-freedom quantum memory. Nat Commun, 2018, 9: 3407
122 Xu Z, Wu Y, Tian L, et al. Long lifetime and high-fidelity quantum memory of photonic polarization qubit by lifting zeeman degeneracy. Phys Rev Lett, 2013, 111: 240503
123 Nicolas A, Veissier L, Giner L, et al. A quantum memory for orbital angular momentum photonic qubits. Nat Photon, 2014, 8: 234–238
124 Vernaz-Gris P, Huang K, Cao M, et al. Highly-efficient quantum memory for polarization qubits in a spatially-multiplexed cold atomic ensemble. Nat Commun, 2018, 9: 363
125 Honda K, Akamatsu D, Arikawa M, et al. Storage and retrieval of a squeezed vacuum. Phys Rev Lett, 2008, 100: 093601
126 Appel J, Figueroa E, Korystov D, et al. Quantum memory for squeezed light. Phys Rev Lett, 2008, 100: 093602
127 Ding D S, Zhang W, Zhou Z Y, et al. Quantum storage of orbital angular momentum entanglement in an atomic ensemble. Phys Rev Lett, 2015, 114: 050502
128 Yan Z, Wu L, Jia X, et al. Establishing and storing of deterministic quantum entanglement among three distant atomic ensembles. Nat Commun, 2017, 8: 718
129 Yuan Z S, Chen Y A, Zhao B, et al. Experimental demonstration of a BDCZ quantum repeater node. Nature, 2008, 454: 1098–1101
130 Chen L K, Yong H L, Xu P, et al. Experimental nested purification for a linear optical quantum repeater. Nat Photon, 2017, 11: 695–699
131 Kalb N, Reiserer A A, Humphreys P C, et al. Entanglement distillation between solid-state quantum network nodes. Science, 2017, 356: 928–932
132 Bhaskar M K, Riedinger R, Machielse B, et al. Experimental demonstration of memory-enhanced quantum communication. Nature, 2020, 580: 60–64
133 Yu Y, Ma F, Luo X Y, et al. Entanglement of two quantum memories via fibres over dozens of kilometres. Nature, 2020, 578: 240–245
134 Azuma K, Tamaki K, Lo H K. All-photonic quantum repeaters. Nat Commun, 2015, 6: 6787
135 Buterakos D, Barnes E, Economou S E. Deterministic generation of all-photonic quantum repeaters from solid-state emitters. Phys Rev X, 2017, 7: 041023
136 Li Z D, Zhang R, Yin X F, et al. Experimental quantum repeater without quantum memory. Nat Photon, 2019, 13: 644–648
137 Hasegawa Y, Ikuta R, Matsuda N, et al. Experimental time-reversed adaptive Bell measurement towards all-photonic quantum repeaters. Nat Commun, 2019, 10: 378
138 Ren J G, Xu P, Yong H L, et al. Ground-to-satellite quantum teleportation. Nature, 2017, 549: 70–73

139 Zhang Q Y, Xu P, Zhu S N. Quantum photonic network on chip. Chin Phys B, 2018, 27: 054207
140 Wang J, Paesani S, Ding Y, et al. Multidimensional quantum entanglement with large-scale integrated optics. Science, 2018, 360: 285–291
141 Qiang X, Zhou X, Wang J, et al. Large-scale silicon quantum photonics implementing arbitrary two-qubit processing. Nat Photon, 2018, 12: 534–539
142 Feng L T, Zhang M, Xiong X, et al. On-chip transverse-mode entangled photon pair source. npj Quantum Inf, 2019, 5: 2
143 Llewellyn D, Ding Y, Faruque I I, et al. Chip-to-chip quantum teleportation and multi-photon entanglement in silicon. Nat Phys, 2020, 16: 148–153
144 Masada G, Miyata K, Politi A, et al. Continuous-variable entanglement on a chip. Nat Photon, 2015, 9: 316–319
145 Lenzini F, Janousek J, Thearle O, et al. Integrated photonic platform for quantum information with continuous variables. Sci Adv, 2018, 4: eaat9331
146 Otterpohl A, Sedlmeir F, Vogl U, et al. Squeezed vacuum states from a whispering gallery mode resonator. Optica, 2019, 6: 1375
147 Tang H, Franco C D, Shi Z Y, et al. Experimental quantum fast hitting on hexagonal graphs. Nat Photon, 2018, 12: 754–758