All photonic quantum repeaters

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Quantum communication holds promise for unconditionally secure transmission of secret messages [1, 2] and faithful transfer of unknown quantum states [3]. Photons appear to be the medium of choice for quantum communication. Owing to photon losses—which increase exponentially with the communication distance, long-distance quantum communication necessitates quantum repeaters [4]. A necessary and highly demanding requirement for quantum repeaters [4–18] is now clarified [19] to be the existence of *matter quantum memories* [4, 7, 9–11, 14–18] that satisfy not only Divincenzo's five criteria for universal quantum computation but also his (really hard) extra criterion [20]. Therefore, as long as quantum repeaters need to use matter quantum memories, they may be more difficult than universal quantum computation, which will remain undeniable in theory, i.e., without a future experimental breakthrough.

Here we show [21] that such a demanding requirement is, in fact, unnecessary by introducing the concept of *all photonic* quantum repeaters. As an example of the realization of this concept, we present a protocol based only on linear optical elements, single-photon sources, photon detectors, and active feedforwards, similarly to optical universal quantum computation [22–24].

We draw the protocol from a concept, "time reversal," underlying significant findings in quantum information theory, such as the measurement-based quantum computation [25, 26] and the measurement-device-independent quantum key distribution [27]. In particular, our protocol corresponds to the time reversal of the conventional quantum repeaters [4–15, 18], where entanglement swapping is performed *before* entanglement generation. This is an innovative part of our proposal. As an example to achieve such a time-reversed quantum repeater, we use cluster-state [26] flying qubits rather than simple Bell pairs, in contrast to existing quantum repeaters [4–15, 18]. Since

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our protocol is the time-reversed version of a conventional quantum repeater with a polynomial scaling for the communication distance, our protocol follows the same scaling.

The all photonic nature of our protocol presents the following advantages that should be distinguished from ones of quantum repeaters based on matter quantum memories: (a) No need of matter quantum memories implies that the protocol requires no waiting time. As a result, our protocol can achieve the highest repetition rate in theory, i.e., the rate whose bottleneck is just determined by the slowest device in the protocol. (b) All the assumed optical components are available and simpler and better understood than matter quantum memories. For instance, matter quantum memories can be diverted [5, 12, 28] to single-photon sources, but the converse is not true. (c) Coherent frequency converters for photons to increase the coupling to matter quantum memories [29] and to optical fibers [30], although which have been essential in the conventional schemes, are unnecessary. (d) The protocol is rigorously proved to be much easier to be achieved than quantum computing through a fair comparison with KLM scheme. (e) The protocol could work at room temperature. Therefore, our result paves a completely new route toward quantum repeaters with efficient single-photon sources rather than matter quantum memories. Even from a fundamental viewpoint, the all photonic feature of our theory enables single photons to fully describe even quantum repeaters in addition to quantum computation [22–24] and boson sampling [31], which clarifies the potential of single photons as unified and fair language to express complexity of any kind of quantum information processing.

Details of our work can be found in Ref. [21].

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