Quantum repeater without Bell measurements in double-quantum-dot systems

Xiao-Feng Yi 1 · Peng Xu 1 · Qi Yao 1 · Xianfu Quan 2,3

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Abstract
We propose a Bell measurement-free scheme to implement a quantum repeater in GaAs/AlGaAs double-quantum-dot systems. We prove that four pairs of double quantum dots compose an entanglement unit, given that the initial state is singlet states. Our scheme differs from the famous Duan–Lukin–Cirac–Zoller (DLCZ) protocol in that Bell measurements are unnecessary for the entanglement swapping, which provides great advantages and conveniences in experimental implementations. Our scheme significantly improves the success probability of quantum repeaters based on solid-state quantum devices.

Keywords Entanglement swapping · DLCZ protocol · Double quantum dot · Quantum repeater

1 Introduction
Quantum repeater is a basic building block in quantum communication, quantum computing, and quantum teleportation. After the original ideal of the quantum repeater by Briegel et al. [1] in 1998, Duan et al. [2] presented the widely adopted DLCZ scheme, which is based on atomic ensembles and linear optics with many Bell measurements. Shortly, the robustness of a quantum repeater was analyzed by Zhao et al. [3] and Jiang et al. [4]. Numerous quantum repeater schemes to further enhance the noise-resistance are proposed. Among all these schemes, photons act as information carriers and Bell
measurements are required. Similar to the DLCZ scheme, the probability of the successful entanglement swapping in such schemes is $50\%$ [5]. To improve the success probability, entanglement purification is also adopted [6].

There are many physical systems serving as candidates to realize quantum information processing [7], for example, trapped ions, quantum dots (QDs), photons, neutral cold atoms in optical lattice, nitrogen vacancy centers [8] in diamond, and superconducting qubits [9]. Among these systems, we focus on the semiconductor QDs with the aid of optical cavities. The QD is often called artificial atom, which consists of electrons or holes confined in a potential well. There are various types of QDs [10], such as semiconductor QDs (InAs or GaAs), graphene QDs, and so on. We specifically take the semiconductor QDs into consideration in this paper, which are constructed by heterostructures of GaAs and AlGaAs grown with the molecular beam epitaxy technique [11].

QDs have been employed to realize a quantum repeater. In 2014, Wang et al. [12] presented a scheme to construct a quantum repeater based on QDs. In 2015, Wang et al. [13] achieved scalable entangled photon sources with self-assembled QDs in experiment, which gives one a hope to implement a quantum repeater in QDs. However, these schemes are based on photons and Bell measurements. Realizing entanglement between two distant QDs is still absent [14,15].

In this paper, we present an alternative scheme of a quantum repeater which is based on the double quantum dots (DQDs). Different from previous proposals, our scheme employs the product of local measurements on QD electron spins, instead of the Bell measurements of photons. Such local measurements are easier to implement than Bell measurements in QD experiments. In fact, our scheme is divided into three steps: (i) preparation of entanglement pairs in DQDs; (ii) creation of entanglement swapping between 4 QDs, with the help of optical cavities [16] which couple the adjacent DQDs [17–21]; (iii) extending the distance of entangled DQDs many times to realize a quantum repeater, as shown in Figs. 1a, 5.

2 Quantum repeater based on DQDs

2.1 Preparation of initial $(1, 1)$ singlet states

We consider a quantum repeater implemented with many DQDs which are initialized in a $(1, 1)$ singlet state (Bell state) for each DQD. Figure 1b is a schematic diagram of a typical DQD. To prepare the initial singlet state in a DQD, as shown in Fig. 3a, we consider two electrons in the DQD. The charge configurations include $(0, 2)$ and $(1, 1)$, and two electrons are both in the right QD and each in a QD, respectively. For the $(0, 2)$ charge configuration with a large bias (detuning) $\Delta$, the ground state of the DQD is a singlet state $(0, 2)_S$ due to the Pauli exclusion principle, as shown in Fig. 2a. For the $(1, 1)$ charge configuration at zero bias (detuning) $\Delta$, two spin states, a singlet state $(1, 1)_S$, and three triplet states $(1, 1)_T$, are possible. To control bias $\Delta$ in experiments, the gate voltages on gate L and gate R are necessary. By adiabatically and appropriately reducing the bias $\Delta$ in a magnetic field which splits the triplet states of the electrons as shown in Fig. 2b, one reaches the singlet state where the two electron
2.2 Entanglement swapping in a pair of DQDs

After the first step of preparing many \((1, 1)_S\) DQD singlet states, many locally entangled electron spin pairs have been produced, and we need to extend the distance of the entangled pair. As a second step, we extend the entanglement distance from DQD to a pair of DQD, i.e., building the entanglement between the electron spins in QD 1 and QD 4. We choose the well-known entanglement swapping method, which can be achieved by coupling the middle QDs 2 and 3 equally with a single-mode cavity system [19], as shown in Fig. 3a. This procedure is described by the famous Tavis–Cummings model (TCM) [22], whose Hamiltonian is:
Fig. 2  
(a) Preparation diagram of a singlet state $(1, 1)_S$ in a DQD. 
(b) Energy levels of the $(1, 1)$ state in a finite magnetic field. The triplet states are split by the Zeeman energy of the field.

Fig. 3  
(a) Entanglement swapping in two pairs of DQDs. The QDs 2 and 3 are coupled within a cavity. 
(b) Entanglement is established between QD 1 and QD 8, 
(c) Entanglement is established between QD 1 and QD 16.

\begin{equation}
H = \omega a^\dagger a + \frac{1}{2} \omega_2 \sigma_2 Z + \frac{1}{2} \omega_3 \sigma_3 Z + \sum_{i=2,3} g (a^\dagger \sigma_i^- + a \sigma_i^+) \tag{1}
\end{equation}

where $\omega$ is the single-mode frequency of the cavity, $\omega_{2,3}$ is the Zeeman splitting of the electron spin in QD2 and QD3 (we assume $\omega_2=\omega_3$), respectively, and $g$ is the coupling strength between the QDs and the cavity. The annihilation operator of the cavity mode is $a$, and $\sigma_i^+ = |e\rangle_i \langle g|$ and $\sigma_i^- = |g\rangle_i \langle e|$, where $|g\rangle_i$ and $|e\rangle_i$ are the ground state and excited state of the $i$th QD, respectively. We have set $\hbar = 1$.

In the interaction picture defined by $H_0 = \omega a^\dagger a + \frac{1}{2} \omega_2 \sigma_2 Z + \frac{1}{2} \omega_3 \sigma_3 Z$, the Hamilton of the system under the rotating wave approximation can be written as:
\[ H_i = g \sum_{i=2,3} (e^{-i\Delta t} a_i^+ \sigma_i^- + H.c) \] (2)

where \( \Delta \) is the detuning between the cavity frequency \( \omega \) and the QD transition frequency \( \omega_i \). There is no energy exchange between the cavity and QDs in the case \( \Delta \gg g \). By further employing the Nakajima Transformation [19], we obtain the effective Hamiltonian

\[
H = \lambda \sum_{i=2,3} \left( |e\rangle_{ii} \langle e| a a^+ - |g\rangle_{ii} \langle g| a^+ a \right) \\
+ (\sigma_2^+ \sigma_3^- + \sigma_3^+ \sigma_2^-)
\] (3)

with \( \lambda = g^2 / \Delta \). Suppose that the cavity is prepared in a vacuum state, the effective Hamiltonian is then reduced to [19]:

\[
H = \lambda \sum_{i=2,3} |e\rangle_{ii} \langle e| + (\sigma_2^+ \sigma_3^- + \sigma_3^+ \sigma_2^-)
\] (4)

Under such the Hamiltonian, the QD \( i \) and QD \( j \) with an initial product state, such as \( |ee\rangle_{ij}, |eg\rangle_{ij}, |ge\rangle_{ij} \) and \( |gg\rangle_{ij} \), becomes after a period time \( t \), respectively,

\[
|eg\rangle_{ij} \rightarrow e^{-i\lambda t} \left[ \cos(\lambda t) |eg\rangle_{ij} - i \sin(\lambda t) |ge\rangle_{ij} \right], \\
|ee\rangle_{ij} \rightarrow e^{-i2\lambda t} |ee\rangle_{ij}, \\
|gg\rangle_{ij} \rightarrow |gg\rangle_{ij}.
\] (5)

The initial four QDs are in a product state of a pair of singlet states, i.e.,

\[
\psi_{1,2,3,4} = \psi_{1,2} \otimes \psi_{3,4}
\] (6)

with

\[
\psi_{1,2} = \frac{1}{\sqrt{2}} (|eg\rangle - |ge\rangle)_{1,2}, \\
\psi_{3,4} = \frac{1}{\sqrt{2}} (|eg\rangle - |ge\rangle)_{3,4}.
\] (7)

After an evolution time \( t \), the state of four QDs evolves to

\[
|\psi\rangle_{1,2,3,4} = \frac{1}{2} \left\{ |ge\rangle_{1,4} e^{-i\lambda t} \left[ \cos(\lambda t) |eg\rangle_{2,3} - i \sin(\lambda t) |ge\rangle_{2,3} \right] \\
- e^{-i2\lambda t} |gg\rangle_{1,4} |ee\rangle_{2,3} - |ee\rangle_{1,4} |gg\rangle_{2,3} \\
+ |eg\rangle_{1,4} e^{-i\lambda t} \left[ \cos(\lambda t) |ge\rangle_{2,3} - i \sin(\lambda t) |eg\rangle_{2,3} \right] \right\}.
\] (8)
At a special moment $\lambda t = \pi/4$, the above state Eq. (8) turns into

$$|\psi\rangle_{1,2,3,4} = \frac{1}{2} \left\{ e^{i\pi/4} |gg\rangle_{1,4}|ee\rangle_{2,3} - |ee\rangle_{1,4}|gg\rangle_{2,3} + e^{-i\pi/4} \frac{\sqrt{2}}{2} (-|eg\rangle_{2,3}|ge\rangle_{1,4} - i|ge\rangle_{1,4}) + e^{-i\pi/4} \frac{\sqrt{2}}{2} |ge\rangle_{2,3}|eg\rangle_{1,4} - i|eg\rangle_{1,4}) \right\}.$$  

(9)

By measuring the state of the QD 2 and 3, there are four possible outcomes: $|gg\rangle_{2,3}, |ee\rangle_{2,3}, |eg\rangle_{2,3},$ and $|ge\rangle_{2,3}$. For the first two results, $|gg\rangle_{2,3}$ and $|ee\rangle_{2,3}$, no entanglement swapping occurs, i.e., QDs 1 and 4 are not entangled. However, if we get one of the last two results $|eg\rangle_{2,3}$ or $|ge\rangle_{2,3}$, the state would collapse into an entangled state between QDs 1 and 4, namely

$$|\psi\rangle_{1,4} = \frac{1}{\sqrt{2}} [|ge\rangle_{1,4} - i|eg\rangle_{1,4}]$$  

(10)

or

$$|\psi\rangle'_{1,4} = \frac{1}{\sqrt{2}} [|eg\rangle_{1,4} - i|ge\rangle_{1,4}]$$  

(11)

As references [23–27] reported, we may take advantage of a similar method to Wu et al. [23] to switch on/off the coupling between the quantum dots and cavity in experiments. Meanwhile, coupling two distant QDs with a microwave resonator had been realized by Guo’s experimental group [28,29].

2.3 Quantum repeater

For a practical quantum repeater, one needs to extend the distance between the two entangled qubits (QDs here) as long as possible. In our protocol, starting from many singlet states of two adjacent QDs, we have proved that the entangled swapping can be achieved, i.e., QD 1 and QD 4 are entangled pairs and the entanglement distance is doubled. Next, we need to extend further the entanglement distance to 8 QDs, 16 QDs and more (Fig.3b), until we find a periodicity of the entanglement.

Next, for an 8 QDs unit, there are 3 possible initial entangled states in this system

\[ (i)\ . \ \psi_L = \psi_R = \psi_{1,4} \]
\[ (ii)\ . \ \psi_L = \psi_R = \psi'_{1,4} \]
\[ (iii) \ . \ \psi_L = \psi_{1,4} , \ \psi_R = \psi'_{1,4} \]

or $\psi_L = \psi'_{1,4} , \ \psi_R = \psi_{1,4} $  

(12)

Here, the notation $L$ represents left QDs (dot1 and dot4), $R$ represents right QDs (dot5 and dot8). The equations (i) and (ii) represent the states in left QD($\psi_L$) and right QD($\psi_R$) in the same entangled state, and equation (iii) represents the left and right QDs in different entangled states.
Case (i)

The initial state is also a product state of two entangled QD pairs

$$\phi = \psi_{1,4} \otimes \psi_{5,8}$$

$$= \frac{1}{2} [ |ge\rangle_{1,8}|eg\rangle_{4,5} - i|gg\rangle_{1,8}|ee\rangle_{4,5}$$

$$- i|ee\rangle_{1,8}|gg\rangle_{4,5} - |eg\rangle_{1,8}|ge\rangle_{4,5}] \quad (13)$$

By switching on the coupling between the cavity and the QDs 4 and 5 [23], the system evolves after a time $$t$$ into

$$\phi' = \frac{1}{2} [ |ge\rangle_{1,8} e^{-i\lambda t} [\cos(\lambda t)|eg\rangle_{4,5} - i \sin(\lambda t)|ge\rangle_{4,5}]$$

$$- ie^{-i2\lambda t} |gg\rangle_{1,8} |ee\rangle_{4,5} - i|ee\rangle_{1,8} |gg\rangle_{4,5}$$

$$- |eg\rangle_{1,8} e^{-i\lambda t} [\cos(\lambda t)|ge\rangle_{4,5} - i \sin(\lambda t)|eg\rangle_{4,5}]]. \quad (14)$$

Choosing $$\lambda t = \pi/4$$, we find

$$\phi' = \frac{1}{2} \left\{ e^{-\frac{\pi i}{8}} [ |ge\rangle_{1,8} + i|eg\rangle_{1,8}] |eg\rangle_{4,5}$$

$$- e^{-\frac{\pi i}{4}} \left[ |eg\rangle_{1,8} + i|ge\rangle_{1,8} \right] |ge\rangle$$

$$- ie^{-\frac{\pi i}{4}} |gg\rangle_{1,8} |ee\rangle_{4,5} - i|ee\rangle_{1,8} |gg\rangle_{4,5} \right\} \quad (15)$$

Similarly, when detecting the states of QDs 4 and 5, we throw away the results if they are $$|gg\rangle_{4,5}$$ or $$|ee\rangle_{4,5}$$. Otherwise, the final state collapses into the entangled states between QDs 1 and 8, namely

$$|\psi\rangle_{1,8} = \frac{1}{\sqrt{2}} (|ge\rangle_{1,8} + i|eg\rangle_{1,8}),$$

$$|\psi\rangle'_{1,8} = \frac{1}{\sqrt{2}} (|eg\rangle_{1,8} + i|ge\rangle_{1,8}). \quad (16)$$

Obviously, the entanglement distance is doubled again.

Case (ii)

In this case, the initial state is

$$\phi = \psi'_{1,4} \otimes \psi_{5,8}$$

$$= \frac{1}{2} [ |eg\rangle_{1,8} |ge\rangle_{4,5} - i|ee\rangle_{1,8} |gg\rangle_{4,5}$$

$$- i|gg\rangle_{1,8} |ee\rangle_{4,5} - |ge\rangle_{1,8} |eg\rangle_{4,5}] \quad (17)$$
By switching on the coupling between the cavity and the QDs 4 and 5 [23], the system evolves after a time $t$ into

$$
\phi' = \frac{1}{2} \left( \langle eg \rangle_{1,8} e^{-i\lambda t} \left[ \cos(\lambda t) \langle ge \rangle_{4,5} - i \sin(\lambda t) \langle eg \rangle_{4,5} \right] \\
- i \langle ee \rangle_{1,8} \langle gg \rangle_{4,5} - i e^{-i2\lambda t} \langle gg \rangle_{1,8} \langle ee \rangle_{4,5} \\
- \langle ge \rangle_{1,8} e^{-i\lambda t} \left[ \cos(\lambda t) \langle eg \rangle_{4,5} - i \sin(\lambda t) \langle ge \rangle_{4,5} \right] \right).$

(18)

Choosing $\lambda t = \pi/4$, we obtain

$$
\phi' = \frac{1}{2} \left\{ e^{-\frac{\pi}{4}i} \left[ \langle eg \rangle_{1,8} + i \langle ge \rangle_{1,8} \right] \langle ge \rangle_{4,5} \\
- e^{-\frac{\pi}{4}i} \left[ \langle ge \rangle_{1,8} + i \langle eg \rangle_{1,8} \right] \langle eg \rangle_{4,5} \\
- i \langle ee \rangle_{1,8} \langle gg \rangle_{4,5} - i e^{-\frac{\pi}{4}i} \langle gg \rangle_{1,8} \langle ee \rangle_{4,5} \right\}.

(19)

After detecting the states of QDs 4 and 5, we discard results if they are $\langle gg \rangle_{4,5}$ or $\langle ee \rangle_{4,5}$. Then, the final state collapses into entangled states between QDs 1 and 8, namely

$$
\psi_{1,8}' = \frac{1}{\sqrt{2}} (\langle eg \rangle_{1,8} + i \langle ge \rangle_{1,8}), \\
\psi_{1,8} = \frac{1}{\sqrt{2}} (\langle ge \rangle_{1,8} + i \langle eg \rangle_{1,8}).

(20)

**Case (iii)**

In this case, the initial state is

$$
\phi = \psi_{1,4} \otimes \psi_{5,8} \\
= \frac{1}{2} \left[ \langle gg \rangle_{1,8} \langle ee \rangle_{4,5} - i \langle ge \rangle_{1,8} \langle eg \rangle_{4,5} \\
- i \langle eg \rangle_{1,8} \langle ge \rangle_{4,5} - \langle ee \rangle_{1,8} \langle gg \rangle_{4,5} \right].

(21)

By switching on the coupling between the cavity and the QDs 4 and 5 [23], the system evolves after a time $t$ into

$$
\phi' = \frac{1}{2} \left[ e^{-i2\lambda t} \langle gg \rangle_{1,8} \langle ee \rangle_{4,5} \\
- i \langle ge \rangle_{1,8} e^{-i\lambda t} \left[ \cos(\lambda t) \langle eg \rangle_{4,5} - i \sin(\lambda t) \langle ge \rangle_{4,5} \right] \\
- i \langle eg \rangle_{1,8} e^{-i\lambda t} \left[ \cos(\lambda t) \langle ge \rangle_{4,5} - i \sin(\lambda t) \langle eg \rangle_{4,5} \right] \\
- \langle ee \rangle_{1,8} \langle gg \rangle_{4,5} \right].

(22)
Choosing \( \lambda t = \pi/4 \), we obtain

\[
\phi' = \frac{1}{2} \left\{ e^{-\frac{\pi}{4}i} |gg\rangle_{1,8} |ee\rangle_{4,5} - |ee\rangle_{1,8} |gg\rangle_{4,5} - e^{-\frac{\pi}{4}i} \left[ |ge\rangle_{1,8} + i |eg\rangle_{1,8} \right] |ge\rangle_{4,5} - e^{-\frac{\pi}{4}i} \left[ |ge\rangle_{1,8} + i |eg\rangle_{1,8} \right] |eg\rangle_{4,5} \right\}. \tag{23}
\]

After detecting the states of QDs 4 and 5, we throw away the results if they are \( |gg\rangle_{4,5} \) or \( |ee\rangle_{4,5} \). Otherwise, the final state collapses into the entangled states between QDs 1 and 8, namely

\[
\psi_{1,8} = \frac{1}{\sqrt{2}} (|eg\rangle_{1,8} + i |ge\rangle_{1,8}),
\]
\[
\psi'_{1,8} = \frac{1}{\sqrt{2}} (|ge\rangle_{1,8} + i |eg\rangle_{1,8}). \tag{24}
\]

By comparing the results of 4 pairs of QDs and 8 pairs of QDs, we find obviously that they have exactly the same form, indicating the periodicity of the quantum repeater. It is straightforward to extend the quantum entanglement for 16 QDs with a product state of a pair of 8 entangled QDs (Fig. 3c). Similarly, there are also 3 cases in the 16 QDs’ system

(i). \( \psi_L = \psi_R = \psi_{1,8} \),

(ii). \( \psi_L = \psi_R = \psi'_{1,8} \),

(iii). \( \psi_L = \psi_{1,8}, \psi_R = \psi'_{1,8} \);

or \( \psi_L = \psi'_{1,8}, \psi_R = \psi_{1,8} \). \tag{25}

Here, the notation \( L \) represents left QDs (dot1 and dot8), \( R \) represents right QDs (dot9 and dot16). The equations (i) and (ii) represent the states in left QD(\( \psi_L \)) and right QD(\( \psi_R \)) in the same entangled state, and equation (iii) represents the left and right QDs in different entangled state.

By repeating this process, it is easy to extend the entanglement distance to 32 QDs and longer. The probability for preparing the initial state in singlet state with QDs is more than 60% [30]. As a matter of fact, the further the distance, the lower the probability of success (see Fig. 4). Ideally, the probability of success satisfies Eq. (26). In the traditional scheme, \( c = 0.5 \). For our QDs system, we take \( c = 0.6 \) and \( c = 1 \). As described above, four pairs of QDs compose an entanglement unit. We only need to prepare numerous four entanglement pairs and connect them. This probability of success is a little higher than other schemes.

\[
p = c \left( \frac{1}{2} \right)^{n-1} \tag{26}
\]

Our scheme of a quantum repeater differs from the traditional DLCZ scheme in 3 aspects (see Fig. 5 as a summary). (i) Our system is based on solid-state QDs which are different from the coupled atoms and photons system. (ii) The start unit of our scheme is 4 entangled QDs which are prepared from 2 pairs of QDs initially in singlet
Fig. 4  The relationship between extended distance and success probability. $c$ is the probability of preparing initial entangled state, $n$ represents the number of entanglement pairs, and $p$ is the probability of success.

Fig. 5  A complete process to establish entanglement between QD 1 and QD 16 (and more distant QDs) through coupling two central QDs within cavities.

states. This is different from the atoms and photons system. (iii) The measurements we need in our scheme are local, instead of the Bell measurement required in the DLCZ scheme. These local measurements are easier to implement in experiments than Bell measurements. Furthermore, the success probability of our scheme is the same as that of DLCZ scheme, which is higher than other schemes based on solid-state systems.

3 Conclusion

In conclusion, we propose a quantum repeater scheme based on the solid-state QDs. The starting unit is 4 entangled QDs with an experimentally prepared two pairs of DQDs in their singlet states. Our scheme reaches the same success probability as the famous DLCZ scheme but without the requirement of the Bell measurements. Such an advantage is more favored for experimentalists due to the simplicity of the scheme.
Quantum repeater is a fundamental block in quantum communication, quantum computing, and quantum teleportation [21]. For a practical quantum repeater, other factors, such as the decoherence, the environmental effect, and the measurement efficiency are still necessary to be included. The performance of quantum repeater schemes in real situations and new methods to improve the success probability of entanglement swapping using entanglement purification [6,31,32] and noise-suppression [33] also demand further explorations.

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