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Scalable Quantum Information Transfer between Individual Nitrogen-Vacancy Centers by a Hybrid Quantum Interface *

Pei Pei(裴培)[1]**, He-Fei Huang(黄鹤飞)[1], Yan-Qing Guo(郭彦青)[1], He-Shan Song(宋鹤山)[2]
[1]*Department of Physics, Dalian Maritime University, Dalian 116026*
[2]*School of Physics and Optoelectronic Engineering, Dalian University of Technology, Dalian 116024*

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We develop a design of a hybrid quantum interface for quantum information transfer (QIT), adopting a nanomechanical resonator as the intermedium, which is magnetically coupled with individual nitrogen-vacancy centers as the solid qubits, while capacitively coupled with a coplanar waveguide resonator as the quantum data bus. We describe the Hamiltonian of the model, and analytically demonstrate the QIT for both the resonant interaction and large detuning cases. The hybrid quantum interface allows for QIT between arbitrarily selected individual nitrogen-vacancy centers, and has advantages of the scalability and controllability. Our methods open an alternative perspective for implementing QIT, which is important during quantum storing or processing procedures in quantum computing.

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Quantum information transfer (QIT) is an important constituent part of quantum computing (QC).[1] During QC, quantum information is required to transfer between qubits within the certain computing procedure, e.g., within the processing or the storing procedure. QIT has been implemented based on cavity quantum electrodynamics,[2−5] linear optics devices,[6] and superconducting (SC) qubits,[7,8] etc. Recently, hybrid quantum computing (HQC)[9,10] has attracted tremendous attention due to the fact that HQC combines advantages of respective physical systems while avoids the disadvantages, and thus provides a promising channel for scalable QC. Therefore, it is desirable to form hybrid architectures to implement QIT. The architecture should be a scalable quantum interface, which allows for QIT between distant qubits through an intermediate system as the data bus. For the qubits, a nitrogen-vacancy (NV) center[11] in diamonds has been considered as one of the most promising candidates, due to the long coherence time and the possibility of coherent manipulation at room temperature. For the data bus, SC resonators[9,10] have shown excellent compatibility for interacting with various systems, such as atoms,[12−15] spins,[16−18] and SC qubits.[7,19,20] Experimentally, relevant efforts have been made to realize strong coupling of an NV center ensemble (NVCE) of electronic spins to an SC resonator.[21,22] Marcos *et al.*[23] demonstrated that the indirect magnetic coupling between an NVCE and a coplanar waveguide (CPW) resonator via an SC flux qubit is much stronger than the direct coupling, and recently this proposal is demonstrated in experiment.[24] The QIT between an SC flux qubit and an NVCE has been implemented.[25] Moreover, the capability of QIT based on the strong coupling between an NVCE and a CPW resonator via a flux qubit has been demonstrated.[26] These efforts reveal the potential of QIT by hybrid quantum interface serving as the quantum memory or quantum processing units during QC. However, a single qubit defined by ensemble of spins is difficult to manipulate directly, meanwhile the spin coherence time would decrease. Moreover, the size of the SC flux qubit limits the number of NV centers in the ensemble, resulting in the limitation of enhancing the coupling strength.[9] Furthermore, previous works mainly adopt SC flux qubits to enhance the coupling.

In this Letter, we propose a hybrid quantum interface to realize QIT between individual spin qubits within NV centers. Each spin qubit is connected to a CPW resonator as the data bus via a nanomechanical resonator (NAMR).[27,28] The NAMR is magnetically coupled with the NV center which is driven by a microwave field, while capacitively coupled with the CPW resonator. A microwave voltage is applied to the NAMR. The respective coupling strength can be controlled independently by the applied voltage and the microwave field. We analytically demonstrate the QIT for the resonant interaction and large detuning cases. The proposed hybrid quantum interface is scalable for multi-qubits plus the CPW resonator integrated in one chip, and the QIT between any two selected NV centers can be achieved.

The scalable hybrid quantum interface is shown in Fig. 1, which consists of a CPW resonator as the data bus to indirectly coupling two arbitrary NV centers in the array as the processing or memory qubits via the respective NAMR. For each NV center, it consists of a nitrogen atom and a vacancy at the nearest neighboring site. The ith NV center is negatively charged and the electron spin ground state is an $S = 1$ triplet with spin states labeled by $|m_{\rm s} = 0, \pm 1\rangle_i$.

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**Corresponding author. Email: peipei@dlmu.edu.cn
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The zero field splitting is $\omega/2\pi \simeq 2.88\,\mathrm{GHz}$.[29] To match the frequencies of the NV center states and the NAMR, a microwave field is applied to each NV center,[27] resulting in the Hamiltonian in the rotating frame as $H_{\mathrm{NV},i} = \sum_{k=\pm1} \hbar\delta_{k,i}|k\rangle_i\langle k| + \hbar\Omega_{k,i}(|0\rangle_i\langle k| + |k\rangle_i\langle 0|)/2$, where $\delta_{\pm,i}$ and $\Omega_{\pm,i}$ denote the detunings and the Rabi frequencies of the two microwave transitions within ith microwave driven NV center. For simplicity, we assume that the NV centers are identical, and $\delta_{+1,i} = \delta_{-1,i} = \delta$ and $\Omega_{+1,i} = \Omega_{-1,i} = \Omega$. The eigenstates of H_{NV} are $|d\rangle = (|-1\rangle - |+1\rangle)/\sqrt{2}$, $|g\rangle = \cos\theta|0\rangle - \sin\theta|b\rangle$, and $|e\rangle = \cos\theta|b\rangle + \sin\theta|0\rangle$, where $|b\rangle = (|-1\rangle + |+1\rangle)/\sqrt{2}$ and $\tan 2\theta = \sqrt{2}\Omega/\delta$. The corresponding eigenvalues are $\omega_d = \delta$ and $\omega_{e,g} = (\delta \pm \sqrt{\delta^2 + 2\Omega^2})/2$. We consider the case that $\delta > 0$ and the lowest energy state is $|g\rangle$. The eigenstates $|g\rangle$ and $|d\rangle$ are used as logic states of the spin qubit.

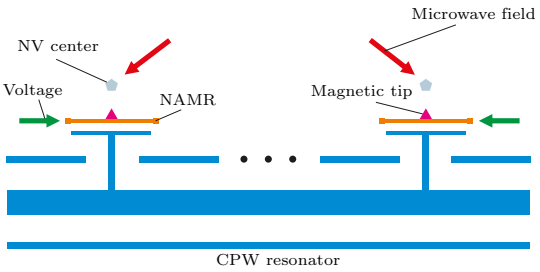

Fig. 1. (Color online) Schematic diagram of the hybrid quantum interface. An array of individual NV centers (silver) are placed along the side of the CPW resonator (blue). Two NV centers of the array are sketched. Through the attached magnetic tip (red), each NV center is magnetically coupled with the NAMR (orange), while driven by an independent microwave field. Each NAMR is capacitively coupled with the CPW resonator, while biased at a microwave voltage (green), respectively. The distance between NV centers is sufficiently large so that the microwave field and voltage applied to each NV center plus NAMR have no effect on others.

Each NAMR is a cantilever or a double clamped beam with the frequency of the lowest nanomechanical mode $\omega_{m,i}$. We consider that the NAMRs are identical and thus governed by the Hamiltonian $H_{\mathrm{NAMR}} = \hbar\omega_{\mathrm{m}} b^\dagger b$, where b ($b^\dagger$) is the annihilation (creation) operator of the phonon in the NAMR. A micromagnetic tip is attached to each NAMR, above which the NV center is placed at a distance h. As the NAMR oscillates, the spin magnetic moment of the NV center is exposed to a time-varying magnetic field $\boldsymbol{B}$. Under the condition that the NAMR displacement $|z|$ is far smaller than the distance h, $B = G_{\mathrm{m}} z_0 (b + b^\dagger)$, where G_{m} is the magnetic field gradient and z_0 is the zero field fluctuation. The Hamiltonian governing the interaction between the NAMR and NV center reads $H_{\mathrm{NV-NAMR}} = -\boldsymbol{\mu}_{\mathrm{NV}} \cdot \boldsymbol{B} = \hbar\lambda(b + b^\dagger)S_z$, where the coupling strength $\lambda = g_{\mathrm{s}}\mu_{\mathrm{b}} G_{\mathrm{m}} z_0$, $g_{\mathrm{s}} \simeq 2$, μ_{b} is the Bohr magneton, and S_z is the z component of the spin operator. By adjusting the frequency difference between $|e\rangle$ and $|d\rangle$, $\omega_{ed} = \omega_e - \omega_d$ is largely detuned with ω_{m}.[30] Under the condition $|\omega_{\mathrm{m}} - \omega_{ed}| \gg \lambda$, the effective Hamiltonian governing the hybrid NAMR-NV center system takes the form

$$H_{\mathrm{int1}} = \hbar\lambda_{\mathrm{s}}(\sigma_- b^\dagger e^{-i\Delta_1 t} + \sigma_+ b e^{i\Delta_1 t}), \tag{1}$$

where $\lambda_{\mathrm{s}} = \lambda\sin\theta$, $\Delta_1 = \omega_d - \omega_g - \omega_{\mathrm{m}}$, $\sigma_+ = |d\rangle\langle g|$ ($\sigma_- = |g\rangle\langle d|$) is the spin raising (lowering) operator of the NV center.

For the CPW resonator, we consider the lowest even mode with the voltage distribution[31] $V(x) = V_0\cos(2\pi x/L)(a + a^\dagger)$, where a ($a^\dagger$) is the annihilation (creation) operator of the photon in the resonator, L is the length of resonator, and $V_0 = \sqrt{\hbar\omega_{\mathrm{r}}/C_{\mathrm{r}}}$ with ω_{r} being the fundamental frequency and C_{r} being the capacitance of the resonator. Each NAMR plus the NV center is located at the voltage antinodes of the even mode, via a displacement dependent capacitance $C_x = C_0(1 + z/d)$. Following the methods in Ref. [32], we apply a microwave voltage $V_x = 2V_{x0}\sin\omega_x t$ to the NAMR and the Hamiltonian governing the CPW-NAMR interaction reads $H_{\mathrm{CPW-NAMR}} = C_0(1 + z/d)(V_x - V(0))^2$, where d is an effective distance between the two resonator electrodes, and ω_x is the driven frequency. Assume that the size of the NAMR is much smaller than the length of the CPW resonator, the Hamiltonian is derived as $H_{\mathrm{CPW-NAMR}} = -2\hbar\lambda_{\mathrm{r}}\sin(\omega_x t)(a + a^\dagger)(b + b^\dagger)$, where the coupling strength $\lambda_{\mathrm{r}} = C_0 V_{x0} V_0 z_0/(\hbar d)$. The effective Hamiltonian governing the hybrid CPW-NAMR system reads

$$H_{\mathrm{int2}} = i\hbar\lambda_{\mathrm{r}}(ab^\dagger e^{i\Delta_2 t} - a^\dagger b e^{-i\Delta_2 t}), \tag{2}$$

where $\Delta_2 = \omega_{\mathrm{r}} - \omega_{\mathrm{m}} - \omega_x$.

The above demonstrations focus on a single NV center indirectly coupling to the CPW resonator via the intermedium NAMR. To realize a hybrid quantum interface for QIT, our model allows for selectively accessing arbitrarily two NV center qubits by applying microwave fields on designated NV centers, since the coupling strength between the NV center and the NAMR $\lambda_{\mathrm{s}}(\theta)$ is dependant on the Rabi frequency Ω of the microwave-NV center system. By properly controlling the microwave fields, the total Hamiltonian governing the system of hybrid CPW-NAMR-2NV centers is described as

$$\begin{aligned} H_{\mathrm{tot}} = \sum_{i=1,2} [&\hbar\lambda_{\mathrm{s}}(\sigma_{i-} b_i^\dagger e^{-i\Delta_1 t} + \sigma_{i+} b_i e^{i\Delta_1 t}) \\ &+ i\hbar\lambda_{\mathrm{r}}(a b_i^\dagger e^{i\Delta_2 t} - a^\dagger b_i e^{-i\Delta_2 t})], \end{aligned} \tag{3}$$

where $i = 1$ and 2 label the designated NV center and corresponding NAMR, respectively.

Now we discuss the realization of QIT with the hybrid quantum interface for both resonant interaction and large detuning cases. For the resonant interaction case, the NAMR is resonant with the microwave modulated NV center, while the CPW resonator is resonant with the voltage biased NAMR, resulting in

$\Delta_1 = \Delta_2 = 0$. Therefore Eq. (3) can be rewritten as

$$H_{\rm I} = \sum_{i=1,2} [\hbar\lambda_{\rm s}(\sigma_{i-} b_i^\dagger + \sigma_{i+} b_i) + i\hbar\lambda_{\rm r}(a b_i^\dagger - a^\dagger b_i)]. \quad (4)$$

We consider the QIT from the first ($i = 1$) NV center to the second ($i = 2$) one, which is described as $(\alpha|g\rangle + \beta|d\rangle)_{\rm NV1}|0\rangle_1|0\rangle_{\rm r}|0\rangle_2|g\rangle_{\rm NV2} \rightarrow |g\rangle_{\rm NV1}|0\rangle_1|0\rangle_{\rm r}|0\rangle_2(\alpha|g\rangle + \beta|d\rangle)_{\rm NV2}$, where NV1, NV2, 1, 2, and r labels the first and the second NV center, the NAMR corresponding to the first and second NV center, and the CPW resonator, respectively, α and β are the normalized probability amplitudes. If the hybrid system is initially prepared in the state $|\Psi(0)\rangle = |d\rangle_{\rm NV1}|0\rangle_1|0\rangle_{\rm r}|0\rangle_2|g\rangle_{\rm NV2}$, the system evolves in the limited subspace spanned by the basis $\{|\psi\rangle_1, |\psi\rangle_2, |\psi\rangle_3, |\psi\rangle_4, |\psi\rangle_5\}$, which read

$$\begin{aligned}
|\psi\rangle_1 &= |d\rangle_{\rm NV1}|0\rangle_1|0\rangle_{\rm r}|0\rangle_2|g\rangle_{\rm NV2},\\
|\psi\rangle_2 &= |g\rangle_{\rm NV1}|1\rangle_1|0\rangle_{\rm r}|0\rangle_2|g\rangle_{\rm NV2},\\
|\psi\rangle_3 &= |g\rangle_{\rm NV1}|0\rangle_1|1\rangle_{\rm r}|0\rangle_2|g\rangle_{\rm NV2},\\
|\psi\rangle_4 &= |g\rangle_{\rm NV1}|0\rangle_1|0\rangle_{\rm r}|1\rangle_2|g\rangle_{\rm NV2},\\
|\psi\rangle_5 &= |g\rangle_{\rm NV1}|0\rangle_1|0\rangle_{\rm r}|0\rangle_2|d\rangle_{\rm NV2}. \quad (5)
\end{aligned}$$

At an arbitrarily given time, the state of the hybrid system reads $|\Psi(t)\rangle = \sum_{i=1}^{5} C_i(t)|\psi\rangle_i$, where $C_i(t)$ are normalized probability amplitudes. With the initial state $|\Psi(0)\rangle$, i.e., $C_1(0) = 1$, $C_i(0) = 0$ ($i = 2$, 3, 4 and 5), we obtain the time-dependant probability amplitudes, by solving the Schrödinger equations, as

$$\begin{aligned}
C_1(t) &= \frac{1}{2}\cos\lambda_{\rm s}t + \frac{\lambda_{\rm r}^2}{\eta^2} + \frac{\lambda_{\rm s}^2\cos\eta t}{2\eta^2},\\
C_2(t) &= -\frac{i}{2}\sin\lambda_{\rm s}t - \frac{i\lambda_{\rm s}\sin\eta t}{2\eta},\\
C_3(t) &= \frac{i\lambda_{\rm s}\lambda_{\rm r}}{\eta^2} - \frac{-i\lambda_{\rm s}\lambda_{\rm r}\cos\eta t}{\eta^2},\\
C_4(t) &= \frac{i}{2}\sin\lambda_{\rm s}t - \frac{i\lambda_{\rm s}\sin\eta t}{2\eta},\\
C_5(t) &= -\frac{1}{2}\cos\lambda_{\rm s}t + \frac{\lambda_{\rm r}^2}{\eta^2} + \frac{\lambda_{\rm s}^2\cos\eta t}{2\eta^2}, \quad (6)
\end{aligned}$$

where $\eta = \sqrt{\lambda_{\rm s}^2 + 2\lambda_{\rm r}^2}$.

Supposing one-qubit information $(\alpha|g\rangle + \beta|d\rangle)_{\rm NV1}$ is encoded in the first NV center, during the evolution governed by the Hamiltonian in Eq. (4), the population of the state $|g\rangle_{\rm NV1}|0\rangle_1|0\rangle_{\rm r}|0\rangle_2|g\rangle_{\rm NV2}$ remains unchanged, while the population of the state $|\psi\rangle_1$ is transferred within the hybrid system. When the population of $|\psi\rangle_1$ evolves to $|\psi\rangle_5$, the QIT from the first NV center to the second one is completed. Therefore we focus on the dynamics of the populations of $|\psi\rangle_1$ and $|\psi\rangle_5$. On the other hand, two kinds of coupling mechanisms, i.e., the NAMR-NV center and the NAMR-CPW resonator, result in two coupling strengths $\lambda_{\rm s}$ and $\lambda_{\rm r}$. To demonstrate the QIT of our methods close to the actual situation, we adopt experimentally feasible parameters,[28] i.e., $\lambda_{\rm s}/2\pi = 240\,{\rm kHz}$ and $\lambda_{\rm r}/2\pi = 430\,{\rm kHz}$. Moreover, the decay rates are considered as follows: single NV center dephasing rate $\Gamma_{\rm s}/2\pi = 2\,{\rm kHz}$, NAMR decoherence rate $\Gamma_{\rm m}/2\pi = 28\,{\rm kHz}$, and CPW resonator decay rate $\kappa/2\pi = 20\,{\rm kHz}$, the couplings are thus in the strong coupling regime. We plot the dynamics of the populations of $|\psi\rangle_1$ and $|\psi\rangle_5$ in Fig. 2.

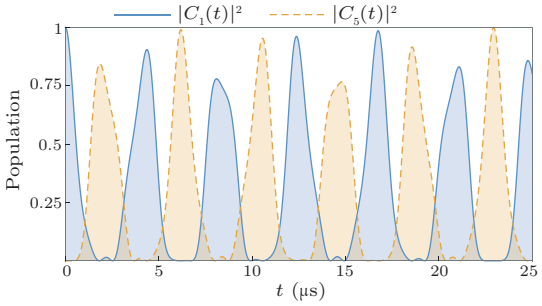

Fig. 2. (Color online) Dynamics of populations of $|\psi\rangle_1$ and $|\psi\rangle_5$. Solid blue curve denotes $|C_1(t)|^2$ and dashed orange curve denotes $|C_5(t)|^2$, respectively. The coupling strengths are given as $\lambda_{\rm s}/2\pi = 240\,{\rm kHz}$ and $\lambda_{\rm r}/2\pi = 430\,{\rm kHz}$, respectively.

Figure 2 clearly shows after a short time, e.g., $\sim$6 μs, $\sim$23 μs, the population of $|\psi\rangle_1$ evolves completely to $|\psi\rangle_5$, which means that the component of $|d\rangle_{\rm NV1}$ is completely transferred to $|d\rangle_{\rm NV2}$, and thus the QIT between separated individual NV centers is implemented. Note that the dynamics of populations reveal overall periodicity on a large timescale and with unbalanced values of $\lambda_{\rm s,r}$, e.g., $\lambda_{\rm s} \gg \lambda_{\rm r}$ or $\lambda_{\rm r} \gg \lambda_{\rm s}$, which are infeasible for our model.

For the large detuning case, the large detuning here means that the NAMR is large-detuned from both the NV centers and the CPW resonator. We consider $\Delta_1 = \Delta_2 = \Delta \gg \lambda_{\rm s}, \lambda_{\rm r}$, and $\lambda_{\rm s}/2\pi = \lambda_{\rm r}/2\pi$. Therefore the NAMR constituent of $H_{\rm tot}$ can be adiabatically eliminated and the effective Hamiltonian is obtained as follows:

$$H_{\rm eff} = \sum_{i=1,2} i\hbar\lambda_{\rm eff}[a\sigma_{i+} - a^\dagger\sigma_{i-}], \quad (7)$$

where $\lambda_{\rm eff} = \lambda_{\rm s}^2/\Delta^2$. Equation (7) shows that there is no energy exchange between NAMR and either each NV center or the CPW resonator, and the virtual phonons of the NAMR induces the effective indirect coupling between the two NV centers via the CPW resonator, while avoiding the population loss of the NAMR.

Following similar methods for the resonant interaction case, the QIT process now reads $(\alpha|g\rangle + \beta|d\rangle)_{\rm NV1}|0\rangle_{\rm r}|g\rangle_{\rm NV2} \rightarrow |g\rangle_{\rm NV1}|0\rangle_{\rm r}(\alpha|g\rangle + \beta|d\rangle)_{\rm NV2}$, the population of state $|g\rangle_{\rm NV1}|0\rangle_{\rm r}|g\rangle_{\rm NV2}$ remains unchanged, and the component of state $|d\rangle_{\rm NV1}|0\rangle_{\rm r}|g\rangle_{\rm NV2}$

evolves in the limited subspace spanned by the basis

$$|\phi\rangle_1 = |d\rangle_{\rm NV1}|0\rangle_{\rm r}|g\rangle_{\rm NV2},$$
$$|\phi\rangle_2 = |g\rangle_{\rm NV1}|1\rangle_{\rm r}|g\rangle_{\rm NV2},$$
$$|\phi\rangle_3 = |g\rangle_{\rm NV1}|0\rangle_{\rm r}|d\rangle_{\rm NV2}. \quad (8)$$

The time-dependant quantum state now reads $|\Phi(t)\rangle = \sum_{i=1}^{3} D_i(t)|\phi\rangle_i$. Under the initial conditions, i.e., $D_1(0) = 1, D_2(0) = D_3(0) = 0$, the normalized probability amplitudes are obtained by solving the Schrödinger equations as

$$D_1(t) = \frac{1}{2} + \frac{1}{2}\cos\sqrt{2}\lambda_{\rm eff}t,$$
$$D_2(t) = -\frac{\sqrt{2}}{2}\sin\sqrt{2}\lambda_{\rm eff}t,$$
$$D_3(t) = -\frac{1}{2} + \frac{1}{2}\cos\sqrt{2}\lambda_{\rm eff}t. \quad (9)$$

Following the resonant interaction case, the dynamics of population of $|\phi\rangle_1$ and $|\phi\rangle_3$ are shown in Fig. 3, where the time $\lambda_{\rm eff}t$ is provided in a dimensionless unit. Obviously the QIT between separated individual NV centers can also be implemented.

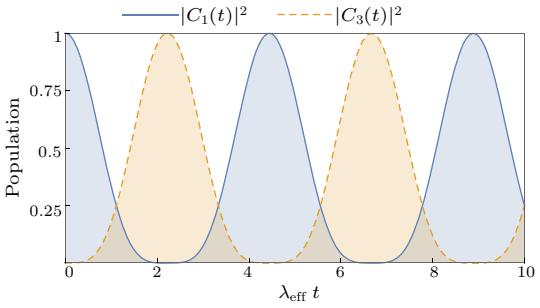

Fig. 3. (Color online) Dynamics of populations of $|\phi\rangle_1$ and $|\phi\rangle_3$. Solid blue curve denotes $|D_1(t)|^2$ and dashed orange curve denotes $|D_3(t)|^2$, respectively. The coupling strengths are given as $\lambda_{\rm s}/2\pi = \lambda_{\rm r}/2\pi = 240\,{\rm kHz}$ and $\Delta = 5\lambda_{\rm s}$, which satisfies the large-detuning condition.

Our proposed hybrid quantum interface has advantages in the scalability and controllability. As shown in Fig. 1, an array of n individual NV centers plus the corresponding NAMR can be placed along the side of the CPW resonator as the data bus, and the whole hybrid system can be integrated in one chip. Selective coupling of CPW resonator and specified NV center can be achieved by applying or removing the microwave fields and biased voltage, through constructing proper pulse sequences. This allows for independently turning on/off $\lambda_{{\rm s},i}$ and $\lambda_{{\rm r},i}$. Therefore arbitrarily two individual NV centers can be indirectly coupled and the QIT between them can be implemented. The architecture also indicates the potential to entangle two or more individual NV centers and implement quantum gating operations. In conclusion, our proposal opens an alternative perspective for implementing QIT between distant individual solid qubits, which is important during quantum storing or processing procedures in QC. Further research may march forward along two paths, the first is to investigate the influence of decoherence on the QIT of the hybrid system, and the second is to extend the hybrid quantum interface to transfer the quantum information out of the memory or processing unit by introducing the optomechanical system.[33]

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