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High-fidelity and robust stimulated Raman transition with parameter-modulated optimal control

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High-fidelity quantum manipulation is of great importance in the field of quantum optics, quantum computing, and quantum simulation [1, 2]. Quantum information transmission between two quantum states in a quantum system or among different quantum systems is of fundamental importance in quantum information science [3]. However, direct quantum state transmission is impossible in most cases, and thus one needs to consult to a intermediate quantum bus [4, 5]. When the bus has long enough coherence time, quantum information transmission can be achieved by resonant coupling. However, for quantum bus with short coherence time, quantum information transmission is implemented by the stimulated Raman transition (SRT) [6–8] technique, i.e., using a two-photon resonant process to avoid the influence of the intermediate bus by decreasing its population. But the two-photon process is a second-order coupling effect that will result in the unwanted Stark shift [9], leading to the imperfect transmission.

Here, we propose a new method that parameter-modulated amplitudes and phases are optimized to realize high-fidelity and robust SRT with optimal control. We employ optimal control algorithms to design pulse parameters of the SRT process to optimize the fidelity of the transmission, which is further confirmed by numerical simulations using optimized parameters. Our methods unfreeze the second-order coupling induced Stark-shift effect of the SRT process and provide a promising way for high-fidelity and robust quantum control toward high-order coupling effect.

To address the problem that the coupling with large detuning between two energy levels can cause unwanted Stark shift, we introduce parameter-modulated Rabi frequencies $\Omega_{0,1}(t)$ and the phases $\phi_{0,1}(t)$ to the system, as shown in Fig. 1a. In this way, it is possible to compen-

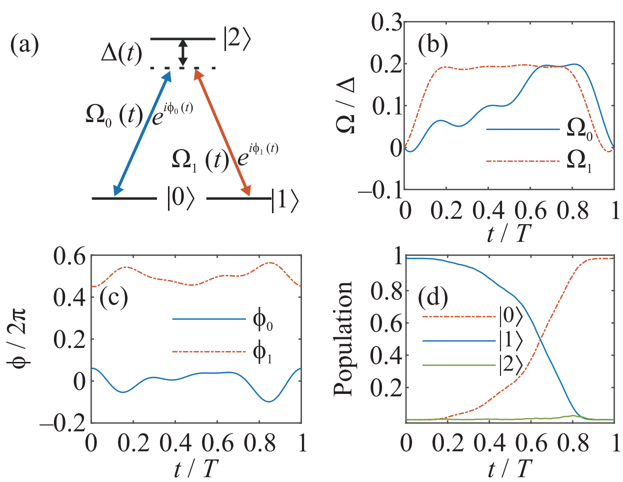

Fig. 1. (Color online) Illustration of our scheme. (a) – Λ-type three-level systems with parameter-modulated Rabi frequencies $\Omega_{0,1}(t)$ and the phases $\phi_{0,1}(t)$. (b) and (c) – Optimal amplitudes and phases of the pulses in relation to time respectively. (d) – The population of each state of the optimized SRT process under decoherence

sate the Stark-shift effect of the SRT process, because parameter-modulated Rabi frequencies and the phases can effectively generate extra phase accumulations. The Hamiltonian of the system in the rotating-wave approximation is written in the basis of $\{|0\rangle, |1\rangle, |2\rangle\}$ as

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$$H(t)=\begin{pmatrix} 0 & 0 & \Omega_0(t)e^{i\phi_0(t)} \\ 0 & 0 & \Omega_1(t)e^{i\phi_1(t)} \\ \Omega_0(t)e^{-i\phi_0(t)} & \Omega_1(t)e^{-i\phi_1(t)} & \Delta(t) \end{pmatrix}. \quad (1)$$

Then, we proceed to implement high-fidelity population transfer of the SRT process. Without loss of generality, we set detuning $\Delta(t)$ as a definite constant Δ and parameterize the Rabi frequencies $\Omega_{0,1}(t)$ and the phases $\phi_{0,1}(t)$ using Fourier series up to Nth order as:

$$\begin{aligned} \Omega_i(t) &= \sum_{n=1}^{N} a_{i_n} \sin\frac{2n\pi t}{T} + b_{i_n}(1-\cos\frac{2n\pi t}{T}), \\ \phi_i(t) &= \sum_{n=1}^{N} c_{i_n} \sin\frac{2n\pi t}{T} + d_{i_n}\cos\frac{2n\pi t}{T}, \end{aligned} \quad (2)$$

where T is the total evolution time, the expansion factors $\{a_{i_n}, b_{i_n}, c_{i_n}, d_{i_n}\}$ are free parameters for the parameterization of the Rabi frequencies $\Omega_{0,1}(t)$ and the phases $\phi_{0,1}(t)$, and index $i = \{0,1\}$, $n = 1 : N$ are referred to control pulses and expansion orders, respectively. The above expansion of pulse envelopes is chosen based on the practical consideration that the drives are inactive at the time boundaries for $\Omega_i(0) = \Omega_i(T) = 0$. This parameterization allows us to introduce optimization algorithm to modulate pulses, thereby converting the problem of control pulse design into an optimization process.

Here, Covariance Matrix Adaptation Evolution Strategy [10], a stochastic and derivative-free approach, is employed for numerical optimization. It generates M arrays of candidate parameters, denoted by $\{\boldsymbol{\lambda}_m = (a^m_{i_n}, b^m_{i_n}, c^m_{i_n}, d^m_{i_n}), m = 1 : M\}$ and selects some of them as parent parameters by the cost function values to generate new iterations. Here, we optimize the population transfer of the SRT process by defining the cost function as the state infidelity. The infidelity of the population transfer of the SRT process is calculated by [11]

$$O(\boldsymbol{\lambda}_m) = 1 - \mathrm{Tr}\left[\sqrt{\sqrt{\rho(\boldsymbol{\lambda}_m)}\rho_0\sqrt{\rho(\boldsymbol{\lambda}_m)}}\right], \quad (3)$$

where ρ_0 is the density matrix of the target state and $\rho(\boldsymbol{\lambda}_m)$ corresponds to the actual final state controlled by parameters $\boldsymbol{\lambda}_m$. Here, we chose the expansion order truncated to $N = 4$, which gives 16 free parameters for each pulse. The Rabi frequencies $\Omega_{0,1}(t)$ and the phases $\phi_{0,1}(t)$ of the control pulses for the optimized solution to cost function of Eq. (3) are plotted in Fig. 1b and c, respectively. Furthermore, numerical result is shown in Fig. 1d, where the state fidelity of the optimized SRT process can realize more higher fidelity of 99.91 % than the conventional SRT process.

In conclusion, we proposed an optimal control method by modulating the amplitude and phase parameters to effectively improve the fidelity and the robustness of the SRT. Our scheme can effectively compensate for the Stark-shift effect and achieve both high fidelity and robust population transfer under the realistic environments. The detail simulation results show that our parameter-modulated method can achieve precise population transfer between coupled spin states and maintain high fidelity despite decoherence. Therefore, our scheme has potential applications for high-fidelity and robust quantum control toward high-order coupling effect.

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