Repeat-until-success distributed quantum computation by using single-photon interference at a beam splitter

Xun-Li Feng,[1,2,3] Jun Qian,[3] L. C. Kwek,[1,2,4] and C. H. Oh[1,2]

[1]*Department of Physics, National University of Singapore, 2 Science Drive 3, Singapore 117542*
[2]*Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543*
[3]*Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*
[4]*Nanyang Technological University, National Institute of Education, 1 Nanyang Walk, Singapore 637616*

(Received 6 February 2007; revised manuscript received 2 May 2008; published 28 July 2008)

A repeat-until-success (RUS) measurement-based scheme for the implementation of the distributed quantum computation by using single-photon interference at a 50:50 beam splitter is proposed. It is shown that the 50:50 beam splitter can naturally project a suitably encoded matter-photon state to either a desired entangling gate-operated state of the matter qubits or to their initial state when the photon is detected. The recurrence of the initial state permits us to implement the desired entangling gate in a RUS way. To implement a distributed quantum computation we suggest an encoding method by means of the effect of dipole-induced transparency proposed recently [E. Waks and J. Vuckovic, Phys. Rev. Lett. **96**, 153601 (2006)]. The effects of the unfavorable factors on our scheme are also discussed.

DOI: 10.1103/PhysRevA.78.012354 PACS number(s): 03.67.Lx, 03.67.Mn, 42.50.Dv

I. INTRODUCTION

Quantum computation employs the principle of coherent superposition and quantum entanglement to solve certain problems with an exponential computational speed up over classical computers. The basic building blocks of a quantum computer are quantum logic gates. Many proposals for realizing the universal two-qubit entangling gates by coherently controlling the qubit-qubit interactions have been presented and some proof-of-principle experiments have been performed. Examples include liquid-state nuclear magnetic resonance [1], trapped ions [2,3], cavity QED [4,5], and quantum dots [6], etc. These proposals successfully demonstrated the principles and the possibilities of the quantum computation. However, it is still a great challenge to scale these implementations which are based on the direct interactions between qubits to the large numbers of qubits because adding more qubits means the modification of the Hamiltonian of the system and thus makes it more complex and difficult to coherently control the qubit-qubit interactions and to individually address the qubits. One possible approach to solve this problem is the *distributed quantum computing* in which the stationary matter qubits act as the registers and the flying qubits, the photons, as buses, and the entangling gates between the matter qubits are implemented by the photon interference effects [7,8] or by feeding the photons from one matter qubit to another [9,10]. Because the qubit-qubit interactions are no longer a necessary condition and the matter qubits are spatially separated, the distributed quantum computing is believed to be scalable to large numbers of matter qubits.

The schemes based on photon interference effects to implement entangling gates for matter qubits [7,8] are always accompanied by the photon measurements and succeed in some cases corresponding to certain photon measurement outcomes with a probability less than unity. To achieve deterministic quantum logic gates, two different methods have been developed at present, one is to resort to the one-way measurement-based quantum computation [11] where certain multiqubit cluster states [12] are initially prepared and the subsequent one-qubit measurements on the selected particles could sufficiently lead to any desired quantum gate operations. The cluster states can be generated probabilistically by photon interference effects and photon measurements. Such proposals [13] have been presented for the improvements on the linear optics quantum computation of the Knill-Laflamme-Milburn (KLM) protocol [14]. It is worth to note that many proof-of-principle linear optics quantum computation proposals have been experimentally realized, such as in the literatures [15,16]. Another method to implement deterministic entangling logic gates is to adopt the *repeat-until-success* (RUS) scheme [8] where the two-qubit entangling gates can be probabilistically implemented by measuring the photons in a mutually unbiased basis when some desired outcomes are observed. Essentially, if the desired measurement outcomes are missed, although one is no longer able to project the final state to an expected gate-operated state any more, the quantum information stored in matter qubits is not destroyed and can be recovered to its original form by some local unitary operations. Thus one can repeat the procedure again and again until a success.

RUS scheme provides an approach for measurement-based quantum computation and may be extended to other measurement-based quantum information processing. In the RUS scheme, in order to achieve a measurement outcome of photons corresponding to either a successful implementation of the gate operation or a recurrence of the original state of the matter qubits, it is a key point to encode the photons to the matter qubits. In their original RUS scheme [8], the authors proposed two methods to encode the photon-matter states by attaching two photons to each qubit. However, both methods need the generation of two single photons on demand in a single qubit encoding procedure and require either to swap each matter qubit twice by laser addressing or to repump the matter qubits, which is really difficult in the practical experiments. To some extent such encoding methods have constrained the advantages of the RUS scheme.

In this work we propose a RUS measurement-based distributed quantum computation scheme by using the single-photon interference at a 50:50 beam splitter. The scheme proposed here can avoid most of the encoding difficulties of the original RUS scheme [8]. In practice our scheme requires neither to individually address the matter qubits in the encoding process nor to execute extra unitary operations to transfer the output states to the gate-operated state or the initial state. Besides, our RUS scheme can be readily generalized to multiqubit cases and can work even in the bad cavity regime. The paper is organized as follows: in Sec. II we show the general principle of RUS scheme by using a beam splitter, Sec. III gives an encoding method for the implementation of controlled-phase (CPhase) gate operation according to the dipole-induced-transparency (DIT) effect, in Sec. IV the effects of the unfavorable factors on our scheme are discussed

II. GENERAL RUS PRINCIPLE BY A BEAM SPLITTER

In this section let us discuss how our RUS scheme works based on the single-photon interference at a beam splitter. Suppose a quantum state $|\Psi\rangle$ is a superposition of two orthogonal states $|\Psi_1\rangle$ and $|\Psi_2\rangle$,

$$|\Psi\rangle = c_1|\Psi_1\rangle + c_2|\Psi_2\rangle, \tag{1}$$

where the coefficients c_1 and c_2 meet the normalized relation. Our aim is to transform the state (1) into a target state with an extra phase factor π in the last term, that is,

$$|\Psi_{\text{tar}}\rangle = c_1|\Psi_1\rangle - c_2|\Psi_2\rangle. \tag{2}$$

This transformation is very important in quantum computation, for example, both the CPhase gate operation and the nonlinear sign gate operation [14] belong to such a transformation.

Suppose one has a method to encode the state (1) with a single photons in the following way:

$$|\Phi_{\text{enc}}\rangle = \hat{b}^\dagger|\text{vac}\rangle \otimes c_1|\Psi_1\rangle + \hat{c}^\dagger|\text{vac}\rangle \otimes c_2 e^{i\phi}|\Psi_2\rangle, \tag{3}$$

where $\hat{b}^\dagger$ ($\hat{c}^\dagger$) is the photon creation operator of the optical field mode $\hat{b}$ ($\hat{c}$), $|\text{vac}\rangle$ is the vacuum state of the optical field, and ϕ is a controllable phase factor in the mode $\hat{c}$. Then the optical modes $\hat{b}$ and $\hat{c}$ are incident upon a 50:50 beam splitter as shown in Fig. 1. The output modes $\hat{d}_1$ and $\hat{d}_2$ are finally detected by photodetectors D_1 and D_2, respectively. The relation between the input modes and the output modes of the 50:50 beam splitter is

$$\hat{d}_1^\dagger = \frac{1}{\sqrt{2}}(\hat{b}^\dagger + i\hat{c}^\dagger),$$

$$\hat{d}_2^\dagger = \frac{1}{\sqrt{2}}(i\hat{b}^\dagger + \hat{c}^\dagger). \tag{4}$$

Therefore after the evolution through the beam splitter, the encoding state (3) becomes

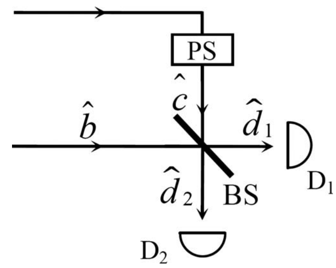

FIG. 1. The setup for the general principle of the RUS scheme by using single-photon interference. PS is a phase shifter, BS is a 50:50 beam splitter, D_1 and D_2 are photodetectors.

$$|\Phi_{\text{enc}}\rangle = \frac{1}{\sqrt{2}}[\hat{d}_1^\dagger|\text{vac}\rangle \otimes (c_1|\Psi_1\rangle - ie^{i\phi}c_2|\Psi_2\rangle) - i\hat{d}_2^\dagger|\text{vac}\rangle \otimes (c_1|\Psi_1\rangle + ie^{i\phi}c_2|\Psi_2\rangle)]. \tag{5}$$

If the photodetector D_1 measures the photon, the state (5) will collapse to $c_1|\Psi_1\rangle - ie^{i\phi}c_2|\Psi_2\rangle$ with 50% probability. Suppose the phase factor ϕ is chosen as $\phi=2k\pi-\pi/2$, with k a positive integer, we thus obtain our target state (2). If, however, the photodetector D_2 measures the photon also with 50% probability, the state (5) will collapse into $c_1|\Psi_1\rangle + ie^{i\phi}c_2|\Psi_2\rangle$, which is exactly the initial state (1) considering $\phi=2k\pi-\pi/2$. Although one cannot realize the target state transformation in the latter case, the initial state (1) is not destroyed and can be used to repeat the above procedure again, in this way one finally realizes a RUS scheme for the tranformation from $c_1|\Psi_1\rangle + c_2|\Psi_2\rangle$ to $c_1|\Psi_1\rangle - c_2|\Psi_2\rangle$ at last.

III. ENCODING FOR CPHASE GATE BASED ON DIT

When applying the above idea to quantum information processing, the choice of $|\Psi_1\rangle$ and $|\Psi_2\rangle$ is determined by the expected quantum operations. Then how to encode the selected initial state (1) according to Eq. (3) is the most important step. In this work, in order to implement a distributed quantum computing by means of our RUS scheme, we suggest an encoding method by using the effect of dipole-induced-transparency (DIT) proposed very recently [17]. Now let us briefly introduce the DIT effect. In a cavity-waveguide coupling system an optical field would be normally transmitted from one waveguide to another through the resonant coupling to the cavity, in other words, the waveguide is normally opaque at the cavity resonance. However, when a dipole (atom, quantum dot, etc.) is placed in the drop-filter cavity, the resonant coupling between the dipole and the cavity makes the waveguide highly transparent *even in the bad cavity regime*, this effect is called DIT. Suppose that the dipole has three relevant states [see Fig. 2(a)], ground state $|0\rangle$, a long-lived metastable state $|1\rangle$, and an excited state $|e\rangle$ with the transition $|1\rangle \leftrightarrow |e\rangle$ resonant to the cavity and the transition $|0\rangle \leftrightarrow |e\rangle$ off resonant to the cavity. In an ideal case, when a photon is sent to one waveguide as plotted in Fig. 2(b), it will be transmitted through the upper or lower waveguides depending on whether dipole is in the state $|1\rangle$ or in $|0\rangle$, that is, $\hat{a}_{\text{in}}^\dagger|\text{vac}\rangle \otimes |1\rangle \to \hat{a}_{\text{out}}^\dagger|\text{vac}\rangle \otimes |1\rangle$ and $\hat{a}_{\text{in}}^\dagger|\text{vac}\rangle \otimes |0\rangle \to -\hat{b}_{\text{out}}^\dagger|\text{vac}\rangle \otimes |0\rangle$, where $\hat{a}_{\text{in}}^\dagger$ and $\hat{a}_{\text{out}}^\dagger$ are, re-

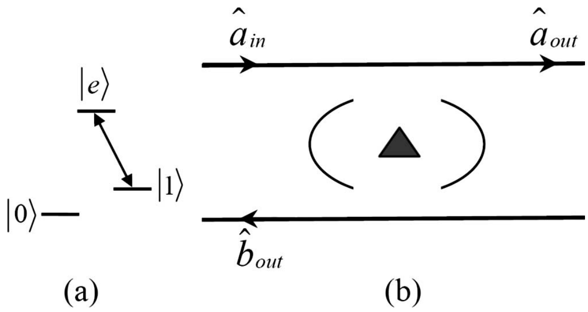

FIG. 2. (a) The level structure of the dipole. (b) DIT effect in the cavity-waveguide system.

spectively, the photon creation operators of the input and output optical field modes in one waveguide, and $\hat{b}_{\text{out}}^{\dagger}$ is the photon creation operator of the output optical field mode in another waveguide. The DIT effect has been proposed to generate and detect Bell states of two dipoles [17] and Greenberger-Horne-Zeilinger (GHZ) states of many dipoles [18].

Figure 3 shows the schematic setup of our RUS scheme for the implementation of a CPhase gate between two dipoles A and B. Both dipoles A and B, which are assumed to be of the same level structure as shown in Fig. 2(a), are placed in the first and the second cavities, respectively. $\hat{a}_{\text{in}}$ and $\hat{a}_{\text{out}}$ stand for, respectively, the input and the output optical field modes in the upper waveguide, $\hat{b}_1$ and $\hat{b}_2$ stand for, respectively, the output optical field modes from the first cavity and the second cavity in the lower waveguides. Before the optical field modes arrive at the beam splitter, the modes $\hat{b}_2$ and $\hat{a}_{\text{out}}$ pass through, respectively, the phase shifters PS_1 and PS_2. The phase shifter PS_1 is chosen in such a way that the modes $\hat{b}_1$ and $\hat{b}_2$ simultaneously arrive at the beam splitter. While PS_2 provides an extra phase delay ϕ in the mode $\hat{a}_{\text{out}}$ in contrast to the modes $\hat{b}_1$ and $\hat{b}_2$. We denote the mode $\hat{a}_{\text{out}}$ after it passes through PS_2 by $\hat{c}$. After interfering at the beam splitter the optical field modes are measured by photodetectors D_1 and D_2.

In our scheme, the states $|0\rangle$ and $|1\rangle$ of the dipoles A and B construct the computational basis $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$,

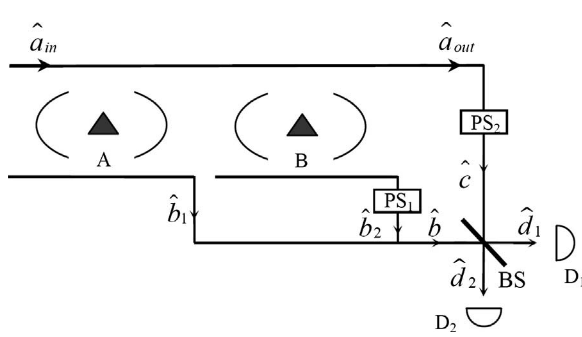

FIG. 3. The schematic setup of the RUS scheme for the implementation of a CPhase gate between dipoles A and B by means of the DIT effect in a cavity-waveguide system. The dipoles A and B are trapped in the first and the second cavities, respectively, PS_1 and PS_2 are the phase shifters. BS and the detectors are the same as that in Fig. 1.

where $|xy\rangle = |x\rangle_A \otimes |y\rangle_B$, with $\{x,y\} = \{0,1\}$ and the subscripts A and B denoting the dipoles A and B, respectively. We suppose the initial state of the two dipoles is

$$|\Psi\rangle_{\text{init}} = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle, \tag{6}$$

where the coefficients α, β, γ, and δ meet the normalized relation. The CPhase gate operation transforms the state (6) into a target state of the form

$$|\Psi\rangle_{\text{tar}} = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle - \delta|11\rangle. \tag{7}$$

Next let us show how to encode the state (6) with a single photon by means of the DIT effect (see Fig. 3). We suppose the input optical field is in a single photon state $\hat{a}_{\text{in}}^{\dagger}|\text{vac}\rangle$. Then the initial state of the input optical field and the dipoles A and B takes the form

$$|\Phi(0)\rangle = \hat{a}_{in}^{\dagger}|\text{vac}\rangle \otimes (\alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle). \tag{8}$$

According to the principle of the DIT effect, the output photon will be from the upper waveguide if and only if both dipoles A and B are in state $|1\rangle$, otherwise the photon will be transmitted along the lower waveguides through the first cavity or the second cavity. When the optical field modes $\hat{b}_1$ and $\hat{b}_2$ arrive at the beam splitter at time t_1, the state (8) will evolve to

$$\begin{aligned}|\Phi(t_1)\rangle &= \hat{b}_1^{\dagger}|\text{vac}\rangle \otimes (\alpha|00\rangle + \beta|01\rangle) + \gamma\hat{b}_2^{\dagger}|\text{vac}\rangle \otimes |10\rangle \\ &\quad + \delta e^{i\phi}\hat{c}^{\dagger}|\text{vac}\rangle \otimes |11\rangle.\end{aligned} \tag{9}$$

Because the optical modes $\hat{b}_1$ and $\hat{b}_2$ arrive at the beam splitter at the same time, they cannot be discriminated from each other, the subscripts in $\hat{b}_1$ and $\hat{b}_2$ can be neglected, and thus Eq. (9) becomes

$$\begin{aligned}|\Phi(t_1)\rangle &= \hat{b}^{\dagger}|\text{vac}\rangle \otimes (\alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle) + \hat{c}^{\dagger}|\text{vac}\rangle \\ &\quad \otimes \delta e^{i\phi}|11\rangle.\end{aligned} \tag{10}$$

Comparing Eq. (10) with Eq. (3), we complete the encoding step for the implementation of the CPhase gate operation for dipoles A and B with $c_1|\Psi_1\rangle = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle$ and $c_2|\Psi_2\rangle = \delta|11\rangle$. Therefore the CPhase gate operation can be realized according to the general principle of the RUS scheme discussed above.

Our RUS scheme can be readily generalized to the multiqubit cases. One can add more cavities in the same way as the second cavity shown in Fig. 3, each containing a dipole and a phase shifter in the lower waveguide. All phase shifters in the lower waveguides are adjusted such that the optical field modes from each cavity simultaneously arrive at the beam splitter. According to the DIT effect, the photon will be exported from the upper waveguide if and only if all the dipoles are in state $|1\rangle$. A similar analysis as done in the case of the two dipoles shows that one can repeat until one successfully obtains multiqubit CPhase gate operations which are locally equivalent to the multiqubit Toffoli gates. Such multiqubit gates might be of great benefit to the error correction codes [19] and the purification of the mixed entangled states [20].

IV. DISCUSSION AND CONCLUSION

Considering the cavity loss, the atomic decay and the limited efficiency of the DIT effect, the fidelity of the resultant entangling gates will be reduced. Actually in the DIT effect the dipole is predominantly in the ground state in the weak excitation limit, so the decay due to the spontaneous emission from the excited state can be neglected. On the other hand, as indicated in Ref. [17], the DIT effect can work even in the case that the vacuum Rabi frequency of the dipole is much smaller than the cavity decay (bad cavity regime), this is extremely important for semiconductor cavity QED because it is hard to achieve a high quality regime by using the technique of the semiconductor. From the point of this view, the DIT-based technique provides us a potential candidate for solid-state quantum computation.

Now let us study the fidelity of the two-qubit CPhase gate operation. In Ref. [17] a general formula about the input-output relation was given under the conditions of cavity decay, dipole decay and some potential leaky modes. In the situations that the cavity resonantly couples to the dipole and to the waveguide with one input field as shown in Fig. 2(b), the input-output relation reads

$$\hat{a}_{\text{out}} = \frac{\left(\frac{1}{2}\kappa + 2\tau g^2\right)\hat{a}_{\text{in}} - \sqrt{\kappa\lambda}\hat{e}_{\text{in}}}{\lambda + \frac{1}{2}\kappa + 2\tau g^2},$$

$$\hat{b}_{\text{out}} = \frac{-\lambda\hat{a}_{\text{in}} - \sqrt{\kappa\lambda}\hat{e}_{\text{in}}}{\lambda + \frac{1}{2}\kappa + 2\tau g^2}, \tag{11}$$

where λ is the coupling constant between the cavity and the waveguide, g the vacuum Rabi frequency of the dipole ($g=0$ when the dipole is in $|0\rangle$), $1/2\tau$ the decay rate of the dipole operator, κ the cavity decay rate, and $\hat{e}_{\text{in}}$ the operator of the potential leaky modes. With the input-output relation (11), the fidelity F, defined as $F=|\langle\psi|\bar{\psi}\rangle|^2$ with $|\bar{\psi}\rangle$ ($|\psi\rangle$) being the outcome state after the photon measurement in the nonideal (ideal) case, can be worked out. Figure 4 plots the fidelity F for one round implementation as a function of λ. According to Ref. [17] the parameters are set $\kappa=0.01$ THz, $g=0.33$ THz, $\tau^{-1}=1$ GHz. The results show that both the gate operation and the recurrent initial state have high fidelities when λ is a few ten times larger than κ.

In the practical experiment, one might obtain an outcome that any photon is not detected by either photon detector in our DIT-based scheme. This situation occurs due to the photon loss during its transmission in the DIT device or to the limited efficiency of the photon detectors. In such a situation, the final state is actually an incoherent mixture of the desired

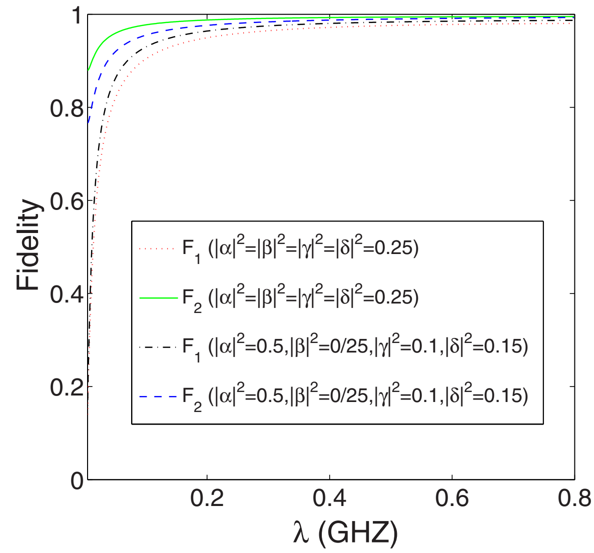

FIG. 4. (Color online). The fidelity for one round operation as a function of λ. F_1 is the fidelity of the CPhase gate operation, F_2 that of the recurrent initial state.

gate-operated state of the matter qubits and their initial state, and our RUS scheme thus fails. From the point of this view, our scheme is not a deterministic one. We have to abandon the results obtained before and restart the quantum computation from the beginning. In order to reduce such unfavorable effects one has to use high quality waveguide and cavities, so that the photon loss can be minimized, and highly sensitive photon detectors. In our scheme the photon detectors are not required to resolve the photon numbers, thus it is sufficient to use bucket or vacuum detectors which discriminate "no photon" from "many photons." From the current technique the bucket detectors can be made more sensitive than number-solving ones [21]. Finally we should point out that any measurement-based quantum computation requires highly precise measurement technique, therefore the realization of a practical quantum computer depends on the developments of the experimental technology.

In conclusion we present a RUS measurement-based distributed quantum computation scheme by using single-photon interference. All the encoding difficulties of the original RUS scheme [8] are overcome by means of the DIT effect encoding approach which can even work in the bad cavity regime. In addition our scheme simplifies the operations and can be readily generalized to a multiqubit situation.

ACKNOWLEDGMENTS

This work was supported by NUS academic research Grant No. WBS: R-144-000-189-305. X.L.F. would also like to acknowledge the support of NSFC Grant No. 60578050.

[1] N. A. Gershenfeld and I. Chuang, Science **275**, 350 (1997).
[2] J. I. Cirac and P. Zoller, Phys. Rev. Lett. **74**, 4091 (1995).
[3] F. Schmidt-Kaler *et al.*, Nature (London) **422**, 408 (2003); D. Leibfried *et al.*, *ibid.* **422**, 412 (2003).
[4] T. Sleator and H. Weinfurter, Phys. Rev. Lett. **74**, 4087 (1995); A. Barenco, D. Deutsch, A. Ekert, and R. Jozsa, *ibid.* **74**, 4083 (1995); T. Pellizzari, S. A. Gardiner, J. I. Cirac, and P. Zoller, *ibid.* **75**, 3788 (1995); P. Domokos, J. M. Raimond, M. Brune, and S. Haroche, Phys. Rev. A **52**, 3554 (1995).
[5] Q. A. Turchette, C. J. Hood, W. Lange, H. Mabuchi, and H. J. Kimble, Phys. Rev. Lett. **75**, 4710 (1995); C. Monroe, D. M. Meekhof, B. E. King, W. M. Itano, and D. J. Wineland, *ibid.* **75**, 4714 (1995); A. Rauschenbeutel, G. Nogues, S. Osnaghi, P. Bertet, M. Brune, J. M. Raimond, and S. Haroche, *ibid.* **83**, 5166 (1999); A. Beige, D. Braun, B. Tregenna, and P. L. Knight, *ibid.* **85**, 1762 (2000).
[6] D. Loss and D. P. DiVincenzo, Phys. Rev. A **57**, 120 (1998).
[7] L.-M. Duan, B. B. Blinov, D. L. Moehring, and C. Monroe, Quantum Inf. Comput. **4**, 165 (2004); X. B. Zou and W. Mathis, Phys. Rev. A **71**, 042334 (2005); S. D. Barrett and P. Kok, *ibid.* **71**, 060310 (2005); J. Cho and H.-W. Lee, Phys. Rev. Lett. **95**, 160501 (2005).
[8] Y. L. Lim, A. Beige, and L. C. Kwek, Phys. Rev. Lett. **95**, 030505 (2005); Y. L. Lim, S. D. Barrett, A. Beige, P. Kok, and L. C. Kwek, Phys. Rev. A **73**, 012304 (2006).
[9] J. I. Cirac, P. Zoller, H. J. Kimble, and H. Mabuchi, Phys. Rev. Lett. **78**, 3221 (1997); S. J. van Enk, J. I. Cirac, and P. Zoller, *ibid.* **78**, 4293 (1997).
[10] A. Serafini, S. Mancini, and S. Bose, Phys. Rev. Lett. **96**, 010503 (2006).
[11] R. Raussendorf and H. J. Briegel, Phys. Rev. Lett. **86**, 5188 (2001); R. Raussendorf, D. E. Browne, and H. J. Briegel, Phys. Rev. A **68**, 022312 (2003).
[12] H. J. Briegel and R. Raussendorf, Phys. Rev. Lett. **86**, 910 (2001).
[13] M. A. Nielsen, Phys. Rev. Lett. **93**, 040503 (2004); D. E. Browne and T. Rudolph, *ibid.* **95**, 010501 (2005).
[14] E. Knill, R. Laflamme, and G. J. Milburn, Nature (London) **409**, 46 (2001).
[15] N. K. Langford, T. J. Weinhold, R. Prevedel, A. Gilchrist, J. L. O'Brien, G. J. Pryde, and A. G. White, Phys. Rev. Lett. **95**, 210504 (2005); N. Kiesel, C. Schmid, U. Weber, R. Ursin, and H. Weinfurter, *ibid.* **95**, 210505 (2005); R. Okamoto, H. F. Hofmann, S. Takeuchi, and K. Sasaki, *ibid.* **95**, 210506 (2005).
[16] R. Prevedel *et al.*, Nature (London) **445**, 65 (2007).
[17] E. Waks and J. Vuckovic, Phys. Rev. Lett. **96**, 153601 (2006).
[18] J. Qian *et al.*, Phys. Rev. A **75**, 032309 (2007).
[19] P. W. Shor, Phys. Rev. A **52**, R2493 (1995).
[20] X.-L. Feng *et al.*, Phys. Lett. A **271**, 44 (2000).
[21] P. Kok, W. J. Munro, K. Nemoto, T. P. Ralph, J. P. Dowling, and G. J. Milburn, Rev. Mod. Phys. **79**, 135 (2007).