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Controlled release of stored optical pulses in an atomic ensemble into two separate photonic channels

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We report an experiment in which optical pulses stored in an atomic system can be controllably released into two different photonic channels. By controllably turning on the retrieve control pulses at either 795 or 780 nm to read the stored optical pulses in a four-level double Λ-type atomic medium, we can obtain the released probe pulse at 795 or 780 nm, respectively. These readout pulses can be further separated spatially and directed into different optical propagation channels through a grating. Such controlled release of stored optical pulses may extend the capabilities of the quantum information storage technique, and can have applications in multichannel all-optical switching, all-optical routing, quantum information processing, and image storage systems.

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In the past few years, storing and releasing photon states in an atomic ensemble by using the effect of electromagnetically induced transparency (EIT) [1] have been proposed theoretically [2] and demonstrated experimentally [3,4]. Subsequent experimental works, such as transporting and time reversing light via atomic coherence [5], observing phase coherence of stored photonic information [6], atomic memory for correlated photon states [7,8], and storing light of arbitrary polarization in atoms [9], have been carried out in the laboratories. Some interesting theoretical schemes, such as the storage and retrieval of light pulses at moderate powers [10], manipulating the retrieval of stored light pulses [11], storing of a pair of pulses of light [12], controlled light storage in a double lambda system [13], and dividing photon memory into two channels in four-level double-EIT systems [14], have also been proposed. These researches have provided good understanding of the physical mechanisms for light storage in coherent atomic assembles.

The light storage experiments were generally carried out in three-level Λ-type atomic systems coupled by two laser beams. As the control light is adiabatically turned off when the probe pulse is in the atomic medium under EIT condition, the state of the probe pulse is mapped into purely atomic spin coherence between the pair of ground states [3,4]. Such photon storage mechanism allows one to transfer optical information between light fields at two different wavelengths by using a four-level double Λ-type atomic system as a storage medium [5,13]. Here, we report an experiment in which we can controllably release the stored light pulse in the atomic medium into the desired one of the two photonic channels in a four-level double Λ-type system, as shown in Fig. 1(a), in a rubidium atomic vapor cell filled with Ne buffer gas.

The present work can be understood qualitatively by considering a four-level double Λ-type configuration of atomic system [as shown in Fig. 1(a)] coupled by a probe field

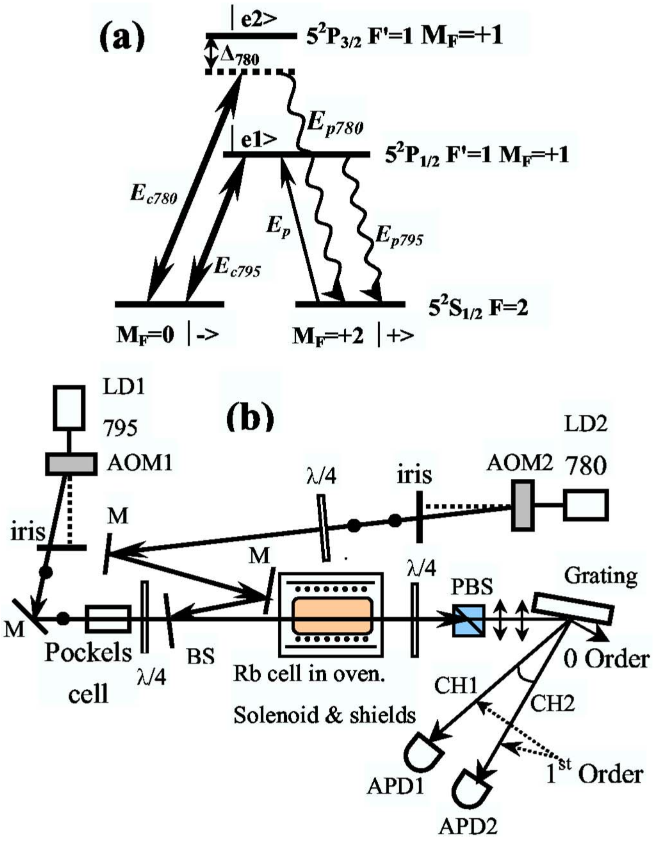

FIG. 1. (Color online) (a) Diagram of the four-level double Λ-type system in ^{87}Rb atom. $\boldsymbol{E}_p$: the input probe laser; $\boldsymbol{E}_{p795}$ and $\boldsymbol{E}_{p780}$: the revived probe photons at 795 and 780 nm, respectively; $\boldsymbol{E}_{c780}$ and $\boldsymbol{E}_{c795}$: the control lasers at 795 and 780 nm, respectively. (b) Schematic of the experimental setup. LD1 and LD2 are extended-cavity diode lasers working at 795 and 780 nm, respectively; AOM1 and AOM2: acousto-optical modulators; M: high reflective mirror; BS: beam splitter; λ/4: quarter-wave plate; PBS: polarizing beam splitter; APD1 and APD2: avalanche photodiode detectors.

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$E_P(\lambda=795\text{ nm})$, a (write and retrieve) control field $E_{C795}(\lambda=795\text{ nm})$, and a retrieve control field $E_{C780}(\lambda=780\text{ nm})$. The probe field E_P (Rabi frequency Ω_p) is right circularly polarized light (σ^-), the control fields E_{C795} (Rabi frequency Ω_{C795}) and E_{C780} (Rabi frequency Ω_{C780}) are left circularly polarized light beams (σ^+). The control field E_{C795} serves as the write control field in light storage process and as the retrieve control field in the readout process. Zeeman sublevels $|5\,^2S_{1/2}, F=2, M_F=0\rangle$ and $|5\,^2S_{1/2}, F=2, M_F=+2\rangle$ are used as the two ground states, labeled as $|-\rangle$ and $|+\rangle$, respectively. States $|5\,^2P_{1/2}, F'=1, M_F=+1\rangle$ and $|5\,^2P_{3/2}, F'=1, M_F=+1\rangle$ serve as the two upper states $|e1\rangle$ and $|e2\rangle$, respectively, in the double-Λ system. The probe field (σ^-) couples the ground state $|+\rangle$ to the lower excited state $|e1\rangle$. The control field $E_{C795}(\sigma^+)$ couples the ground state $|-\rangle$ to the excited state $|e1\rangle$ (D1 line, 795 nm), and the retrieve control field $E_{C780}(\sigma^+)$ couples the ground state $|-\rangle$ to the upper excited state $|e2\rangle$ (D2 line, 780 nm) with a frequency detuning of $\Delta_{780}\approx-190$ MHz. In light storage process, the write control field is adiabatically turned off to convert the state of the input probe pulse into the purely atomic coherence ρ_{-+}. After a certain storage time, the retrieve control field is turned back on and the stored atomic coherence ρ_{-+} is transferred back into the revived probe pulse [4,6]. In the current experiment, if the retrieve control field $E_{C795}(\lambda=795\text{ nm})$ is turned on, the probe pulse at 795 nm is released same as in the typical light storage experiments [3,4,6,7]. However, if the retrieve control field $E_{C780}(\lambda=780\text{ nm})$ is turned on instead of E_{C795}, the released probe pulse is at 780 nm (light pulse generated from state $|e2\rangle$ to state $|+\rangle$. By controllably turning on the retrieve control field E_{C795} or E_{C780}, one can get the released light pulse at either 795 or 780 nm on demand and separate them spatially through a grating.

Our experimental setup is shown in Fig. 1(b). Both LD1 and LD2 lasers are extended cavity diode lasers with several tens of kHz bandwidth and linearly polarized output beams. LD1 laser was tuned to the resonant frequency of $|-\rangle\rightarrow|e1\rangle$ transition, while the LD2 laser (with frequency ω_2) was tuned to the near resonant frequency of $|-\rangle\rightarrow|e2\rangle$ with detuning of $\Delta_{780}=\omega_2-\omega_{F1}\approx-190$ MHz, where ω_{F1} is the frequency of $|-\rangle\rightarrow|e2\rangle$ transition. The acousto-optical modulator AOM1 is used to switch on and off of the LD1 laser to generate a laser pulse. The polarization of this LD1 laser pulse can be slightly rotated by a fast Pockels cell to generate a weak Gaussian-shaped pulse, which serves as the input probe pulse. The polarization of the weak probe pulse is vertical to that of the remaining laser pulse, which serves as the control pulse E_{C795} (D1 line). The input probe and control pulses are changed to circularly polarized beams with a $\lambda/4$ waveplate. The acousto-optical modulator AOM2 is used to turn on and off LD2 laser to generate the retrieve control pulse E_{C780}. The retrieve pulse E_{C780} becomes circularly polarized by using another $\lambda/4$ waveplate. The laser beams from LD1 and LD2 are combined with a beam splitter (BS, transmission is 70%). The angle of incidence on BS is smaller than 5° to ensure the balance of the reflectivity between the two orthogonal linearly polarized laser beams. The laser beams which include the input probe laser beam $E_P(\sigma^-)$ and the control laser beams E_{C795} and $E_{C780}(\sigma^+)$ were collimated and focused onto a ~3-mm spot at the center of a 5-cm-long Rb vapor cell. The input peak powers were about 3 mW for the control pulse E_{C795}, 300 μW for the probe pulse E_P and 500 μW for the retrieve control pulse E_{C780}, corresponding to Rabi frequencies of $\Omega_{C795}=2\pi\times17$ MHz, $\Omega_P=2\pi\times5.4$ MHz, and $\Omega_{C780}=2\pi\times7.0$ MHz, respectively. The temperature of the Rb vapor cell was set at 88 °C, corresponding to an atomic density of $\sim1\times10^{12}\text{ cm}^{-3}$. In order to ensure long lifetime of the atomic spin coherence, the Rb vapor cell is filled with 30 Torr Ne buffer gas and placed in a μ-metal shield to reduce the ambient magnetic field. We also used a precision solenoid to control the static magnetic field along the propagation axis of the laser beam. After leaving the Rb vapor cell, the laser beams go through another $\lambda/4$ waveplate and regain their original linear polarizations. Most of the (write and retrieve) control fields are blocked by a polarizing beam splitter (PBS), and the revived probe pulse whose polarization is perpendicular to that of the control light will pass it. A grating with a groove density of 1800 lines/mm and the first-order diffraction efficiency of 60% was used to spatially separate the revived probe pulses at 795 and 780 nm. The first-order diffraction beam at 795 or 780 nm propagates in CH1 or CH2 and is detected by the avalanche photodiode APD1 or APD2, respectively.

The time sequences of the light storage and release processes are shown in Fig. 2. The traces A, B, and C in Fig. 2(a) correspond to the control field E_{C795}, the probe field E_P, and the retrieve control field E_{C780}, respectively. The intervals of turn-on and turn-off of these fields can be precisely controlled by external logic program. The write control field ($\lambda=795$ nm) is first turned on and most of atoms are prepared to be in the state $|+\rangle$, then a probe pulse with a temporal length of ~25 μs (corresponding to a spatial length of ~7 km in free space) enters into Rb vapor cell. The measured probe pulse delay is about 6.2 μs, corresponding to the group velocity of $V_g\approx8$ km/s. So the probe pulse is spatially compressed by more than 4 orders of magnitude in the 5-cm-long Rb cell. When much of the probe pulse is contained in the Rb vapor cell, we switch off the write control laser beam to store the probe pulse in the collective atomic medium. After a time interval of 50 μs, the retrieve control pulse E_{C795} is launched to release the stored optical pulses. The light pulse at 795 nm is released as in the three-level light storage experiments [3,4]. Traces *E* and *F* in Figs. 2(b) and 2(c) are two traces recorded by APD1 and APD2 detectors, respectively. As shown in Fig. 2(b), the peak I is a part of the probe pulse which has left the Rb cell before the write control field is turned off. This untrapped (or leaked) light pulse is delayed by about ~6.2 μs by the EIT medium as compared to free-space propagation. The observed signal pulse peak II in trace *E* is the revived probe pulse that was stored in the atomic medium for an interval of 50 μs. Trace *F* does not have any revived probe pulse signal in the first process of light storage and releasing since only a recovered signal pulse at $\lambda=795$ nm is generated and deflected into photonic channel 1 through the grating and detected by APD1. Subsequently, a second light pulse storage process is repeated. This time we turn on the retrieve control field E_{C780} instead of E_{C795}, so the recovered probe pulse at 780 nm is released and deflected into photonic channel 2 through the

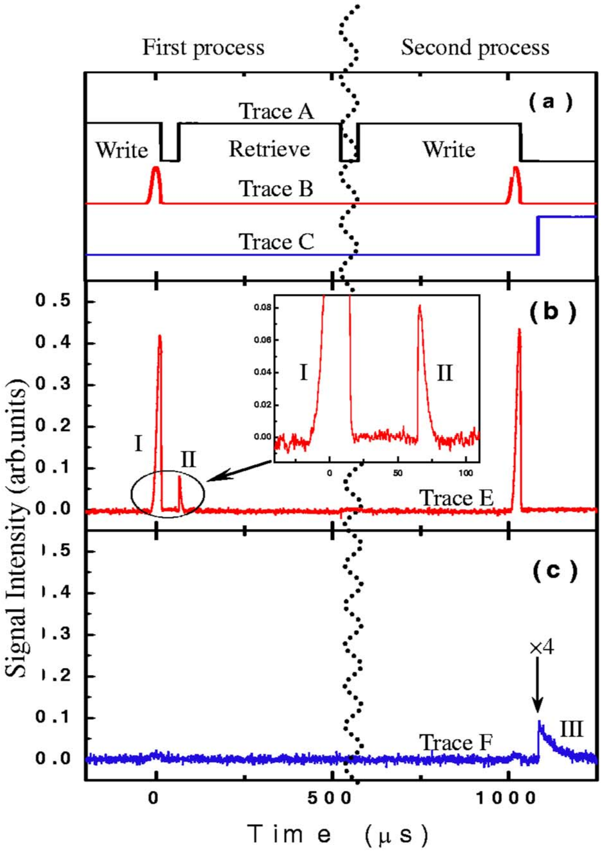

FIG. 2. (Color online) Measured results for a storage time of 50 μs. (a) Controlling time sequences: Trace A, control pulse ($\lambda = 795$ nm); Trace B, probe pulse; Trace C, retrieve control pulse ($\lambda = 795$ nm). (b) Signal recorded by APD1. (c) Signal recorded by APD2. Background transmission from the control field, leaked into the signal field detection optics, has been subtracted from these traces.

grating. The peak III in trace *F* shows the revived probe pulse signal ($\lambda = 780$ nm) detected by APD2. Trace *E* does not have any revived probe pulse signal in the second light release process. In Fig. 3, we show the revived probe pulse which is stored in the atomic medium for a time interval of 100 μs. Traces *G* and *H* in Figs. 3(b) and 3(c) are the recorded signals detected by APD1 and APD2, respectively. The amplitudes of the revived probe pulses in Fig. 3 are reduced due to longer storage time compared to that in Fig. 2.

Figure 4 plots the ratios of peak powers of revived probe pulses at 795 and 780 nm to that of input probe pulse as a function of storage time. From Fig. 4, one can see that both peak powers of the revived probe pulses at 795 and 780 nm decrease as the storage time gets longer due to the atomic decoherence and have approximately the same decline slope. In the absence of buffer gas, the main mechanisms for coherence decay are due to atomic diffusion out of the light beam when light beams are switched off and atomic transient effect due to atoms flying through the laser beams [15]. For a light beam with the diameter of $d = 3$ mm and atoms with the average speed of $\nu = 300$ m/s, the atoms can fly through the laser beam in the time of about $d/\nu = 10$ μs. However,

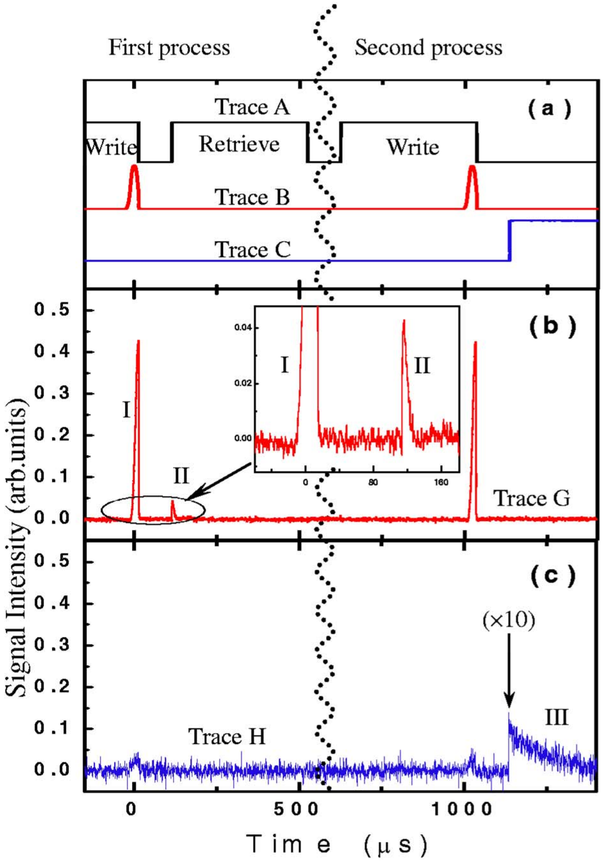

FIG. 3. (Color online) Measured results for the storage time of 100 μs. Other descriptions are same as in Fig. 2.

with buffer gas of appropriate pressure (as in our experiment, the pressure of Ne buffer gas is 30 T), the Rb atoms collide frequently with the buffer gas atoms and diffuse much slower through and out of the light beams. We measured the coherence decay time to be about 110 μs (estimated from Fig. 4), which is consistent with the coherence decay times measured in other optical storage experiments (such as Ref. 4). Of

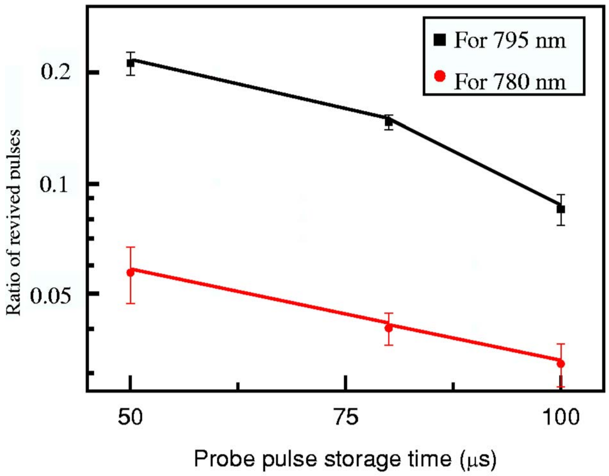

FIG. 4. (Color online) Ratios of peak powers of revived probe pulses at 795 and 780 nm to that of input probe pulse as a function of storage time.

course, other experimental conditions can also contribute to the coherence decay time of the stored optical information, such as buffer pressure (if the pressure of buffer gas gets large, the coherence decay time will become smaller due to spin-exchange collisions [16]), atomic density (cell temperature), leakage of earth magnetic, the angle between coupling and probe beams.

It is worth to note that the amplitude of the revived probe pulse at 795 nm has a larger amplitude and a smaller temporal width than that of the revived pulse at 780 nm in our experiment. This is caused by the fact that the retrieve control field E_{C795} has a larger intensity than that of E_{C780} (the ratio of the Rabi frequencies Ω_{C795} to Ω_{C780} is about 2.5) [3]. In the second release process, we tried to increase the intensity (I_{C780}) of the retrieve control field E_{C780}, but found that the amplitude of the revived probe pulse at 780 nm would not increase and, on the contrary, it became even smaller. We believe that this phenomenon is caused by interacting with other hyperfine atomic levels in the system. In D2 lines of Rb atoms, there is another state $5\,^2P_{3/2}$, $F'=3$. The retrieve control field $E_{C780}(\sigma^+)$ not only interacts with the transition from state $|->$ to state $|e2\rangle$ ($|5\,^2P_{3/2},F'=1,M_F=+1\rangle$) to read out the atomic coherence ρ_{-+}, but also couples the state $|+\rangle$ to state $|5\,^2P_{3/2},F'=3,M_F=+3\rangle$ with a detuning Δ_{OP}, which produces an additional optical pumping. The effect of this additional optical pumping depends on the intensity I_{C780} as well as on the detuning Δ_{OP}. Larger the intensity I_{C780} is, stronger the effect of this additional optical pumping becomes. Such optical pumping process may destruct the atomic coherence ρ_{-+}. In warm Rb atoms, the detuning Δ_{OP} should be greatly beyond the Doppler linewidth Δ_D and the intensity I_{C780} can not be very strong in order to avoid this additional optical pumping. We achieve an optimal revived pulse at 780 nm with a peak power of 0.5 mW and the detuning of $\Delta_{\mathrm{OP}}=(\Delta_{780}-\delta_{13})\approx-(190+424)$ MHz$=-614$ MHz, where δ_{13} is the splitting between the states $5\,^2P_{3/2}F'=1$ and $5\,^2P_{3/2}F'=3$.

We would like to point out that our light signal storage process is different from that reported in Ref. 5. In Ref. 5, the probe and write control pulses are two components (σ^+ and σ^-) of a linearly polarized light pulse, so the intensity and the temporal length of the probe pulse are same as the write control light pulse. In such case the atomic coherence created in this system is always under the CPT condition. While, in our experiment, the probe pulse is weaker than the write control beam, and the temporal length of the probe pulse can be different from the write control pulse. This means that the probe signal storage is based on "dynamic EIT" which allows the optical information in the probe pulse to be linearly, coherently, and reversible mapped into a collective atomic state with high efficiency [4,6]. The retrieving process of the stored optical pulses into two separate photonic channels is an extension of the photon storage techniques in atomic assembles and can be easily expanded to even more retrieving channels. We will further investigate the effect of optical pumping among ground-state Zeeman sublevels on the storage process and the coherent properties of the stored, as well as the retrieved signal pulses.

In conclusion, we experimentally demonstrated that the atomic memory can be controllably released into photonic channels at 795 or 780 nm in a four-level double Λ-type atomic system. The revived probe light pulses at 795 and 780 nm were further separated out and deflected into different paths through a grating. Base on the mechanism of the controllable release of stored light, one can build efficient all-optical routing, multichannel all-optical switch, and image storage systems. For example, by releasing the stored optical pulses into different optical channels (with different wavelength) in a controllable way, one can use it for delayed optical switching/router in optical communication systems, and when the involved photon energy gets down to single-photon level, such system will form the essential delay and switching/routing elements in the proposed quantum networks. Also, compared to the revived light pulse at 795 nm, the amplitude of revived light pulse at 780 nm is smaller and its temporal width is larger due to the limitation of intensity increase of the retrieve control beam ($\lambda=780$ nm), but the optical information is still preserved in the light storage and release processes. By using cold atoms as the storage medium, the Doppler broadening effect can be completely eliminated and the intensity of the retrieve control beam ($\lambda=780$ nm) can increase without producing optical pumping, thus the revived light pulse at 780 nm will better preserve optical information stored in the atomic medium. This process will provide an approach to transfer the state of photons between two light pulses at different wavelengths and can have applications in quantum information processing and quantum networking.

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[1] S. E. Harris, Phys. Today **50**, 36 (1997); J. P. Marangos, J. Mod. Opt. **45**, 471 (1998).

[2] M. Fleischhauer and M. D. Lukin, Phys. Rev. Lett. **84**, 5094 (2000).

[3] C. Liu, Z. Dutton, C. H. Behroozi, and L. V. Hau, Nature (London) **409**, 490 (2001).

[4] D. F. Phillips, A. Fleischhauer, A. Mair, R. L. Walsworth, and M. D. Lukin, Phys. Rev. Lett. **86**, 783 (2001).

[5] A. S. Zibrov, A. B. Matsko, O. Kocharovskaya, Y. V. Rostovtsev, G. R. Welch, and M. O. Scully, Phys. Rev. Lett. **88**, 103601 (2002).

[6] A. Mair, J. Hager, D. F. Phillips, R. L. Walsworth, and M. D. Lukin, Phys. Rev. A **65**, 031802(R) (2002).

[7] C. H. Van der Wal, M. D. Eisaman, A. André, R. L. Walsworth, D. F. Phillips, A. S. Zibrov, and M. D. Lukin, Science **301**, 196 (2003).

[8] C. W. Chou, S. V. Polyakov, A. Kuzmich, and H. J. Kimble, Phys. Rev. Lett. **92**, 213601 (2004).
[9] H. Gao, M. Rosenberry, and H. Batelaan, Phys. Rev. A **67**, 053807 (2003).
[10] Tarak Nath Dey and G. S. Agarwal, Phys. Rev. A **67**, 033813 (2003).
[11] Anil K. Patnaik, F. L. Kien, and K. Hakuta, Phys. Rev. A **69**, 035803 (2004).
[12] A. Raczyński, J. Zaremba, and S. Zielińska-Kanisaty, Phys. Rev. A **69**, 043801 (2004).
[13] A. Raczyński and J. Zaremba, Opt. Commun. **209**, 149 (2002).
[14] A. Joshi and M. Xiao, Phys. Rev. A **71**, 041801(R) (2005).
[15] J. E. Thomas and W. W. Quivers, Jr., Phys. Rev. A **22**, 2115 (1980).
[16] S. Brandt, A. Nagel, R. Wynands, and D. Meschede, Phys. Rev. A **56**, R1063 (1997).