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Versatile, dynamically balanced low-noise optical-field manipulator using a coherently prepared atomic medium

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We propose a versatile dynamic optical-field manipulator using a coherently prepared atomic medium. We show that by locking the pump power change with the two-photon detuning, a π-phase shifting can be realized with unit probe fidelity in a broad two-photon detuning range. The two-photon-insensitive π-phase-shift mode with significantly reduced fluctuation makes this scheme an attractive system for low-noise phase-gate operations.

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Control of phase and intensity of single/few photons using an atomic medium has always been an important research subject with potential applications in quantum information processing and quantum-state manipulation [1,2]. All-optical approaches are particularly desirable because of remarkable advantages of a light field such as monochromaticity, fast propagating velocity, high spatial and temporal coherence, and propagation controllability. In the past two decades, many schemes have been proposed and investigated [3–15]. Many recent studies have shown that electromagnetically induced transparency (EIT)-based schemes can lead to significant nonlinear phase shift in the classical field limit [13,16]. Experimentally, Kerr nonlinear effects arising in an N-type EIT medium [17] and a medium with stored atomic-coherence [18] have been studied for phase-control operation in the classical field limit. In a Raman gain medium, a fast, all-optical, continuously controllable Kerr nonlinear phase gate was demonstrated recently [19]. In addition, fast digital signal processing based on this controllable Kerr gate operation, all-optical multi-logic gate operations and transistor functionalities using a Kerr phase-gate method [20], and high-fidelity fast polarization gate operations have also been demonstrated with record low gate control and switching light powers [21].

Although both EIT- and Raman Gain-based schemes have been widely investigated in atomic media, the direct generalization of these schemes to the single/few photon limit prove to be more problematic. The low fidelity due to the significant probe-field attenuation in EIT media [22–24] and the large quantum noise due to the amplification of the probe field in a Raman gain medium are the main obstacles that prohibit realizing a high-fidelity, low-noise phase shifter in the single/few photon limit.

In this Letter, we propose a three-level system with coherently prepared states for phase-shifting operation. This system, which is a hybrid two-wave mixing process with initial atomic coherence [25–27], has a number of interesting properties. For instance, with suitable operation parameters, it can act as a tow-photon-broadband phase shifter or an attenuator/amplifier with zero phase shift. Specifically, we show that by locking the pump field intensity and two-photon detuning, a π-phase shift can be realized with unit probe fidelity in a broad probe-field frequency range. This two-photon-insensitive π-phase shift can significantly reduce the phase noise associated with a Raman gain process, making it an attractive scheme for high-fidelity, low-noise phase-gate operation. We also show the possibility to realize a zero-phase dynamic light attenuator/amplifier and a total transparency with zero phase shift in a Raman gain medium. Physically, this scheme can be viewed as a hybrid scheme in which two processes of different physical principles are allowed to interfere to achieve the desired application functionalities.

The scheme under investigation is a three-state atomic medium interacting with a pump and a weak probe field. The two lower states are assumed to have been coherently prepared prior to the injection of the pump and probe fields (see Fig. 1). The equations of motion for the slowly varying density matrices elements are (neglecting ρ_{22} terms in the first-order perturbation treatment)

$$\dot{\tilde{\rho}}_{21} - i\delta\tilde{\rho}_{21} \approx i\Omega_{21}\rho_{11} + i\hat{\Omega}_{23}\tilde{\rho}_{31} - \gamma_{21}\tilde{\rho}_{21} + \hat{F}_{21}, \quad \textbf{(1a)}$$

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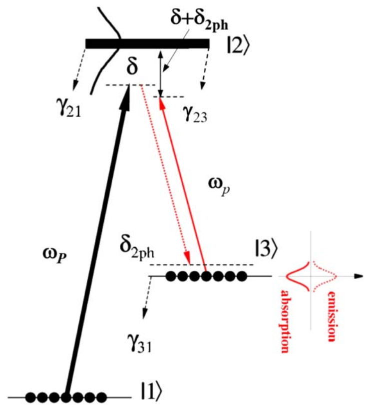

Fig. 1. Three-level scheme where two lower states are coherently prepared prior to the injection of a strong pump field E_P and weak quantum probe field $\hat{E}_p$.

$$\dot{\tilde{\rho}}_{23} - i(\delta + \delta_{2ph})\tilde{\rho}_{23} \approx i\hat{\Omega}_{23}\rho_{33} + i\Omega_{21}\tilde{\rho}_{13} - \gamma_{23}\tilde{\rho}_{23} + \hat{F}_{23}, \tag{1b}$$

$$\dot{\tilde{\rho}}_{13} + i\delta_{2ph}\tilde{\rho}_{13} \approx i\Omega_{12}\tilde{\rho}_{23} - i\hat{\Omega}_{23}\tilde{\rho}_{12} - \gamma_{13}\tilde{\rho}_{13} + \hat{F}_{13}, \tag{1c}$$

where δ and δ_{2ph} are the (large) one- and (small) two-photon detunings, $\Omega_{21} = \Omega_P = D_{21}E_P/\hbar$ is the Rabi frequency of a classical pump field E_P, and $\hat{\Omega}_{23} = \hat{\Omega}_p = D_{23}\hat{E}_p/\hbar$ is the Rabi frequency of the quantum probe-field operator $\hat{E}_p$. Operator $\hat{F}_{nm}$ describes the quantum noise to the density matrix operator $\tilde{\rho}_{nm}$ [28].

To examine the optical response of the system, we first neglect quantum fluctuations. For a large one-photon detuning, Eq. (1a) yields the adiabatic approximation $\tilde{\rho}_{21} \approx -\Omega_{21}\rho_{11}/(\delta + i\gamma_{21})$. Solving Eqs. (1b) and (1c) using the time-Fourier-transform method, we obtained the Fourier transform of the density matrix element $\tilde{\rho}_{23}$ that describes the propagation dynamics of the probe field, $\hat{\mathcal{R}}_{23}(\omega) = \mathcal{D}(\omega)\hat{W}(\omega) = i\hat{W}(\omega)\frac{C(\omega)}{B(\omega)}$, where $\hat{W}(\omega)$ is the Fourier transform of the quantum probe field $\hat{\Omega}_p$, $C(\omega) = (-i\omega + i\delta_{2ph} + \gamma_{13})\rho_{33} - i|\Omega_{21}|^2/(\delta - i\gamma_{23})\rho_{11}$, and $B(\omega) = |\Omega_{21}|^2 + (i\omega - i\delta_{2ph} - \gamma_{13})(i\omega + i\delta - \gamma_{23})$. Physically, the first term in C represents the absorption process starting from $|3\rangle$, whereas the second term denotes the Raman gain process starting from the ground state $|1\rangle$. This dispersion function contains all the physics of a three-state Λ-scheme including EIT and Raman processes depending on the relative sizes of the detunings and pump/driving fields. In accord with the assumption of prepared states, we assume in the following calculation that $\rho_{11} \gg \rho_{22}$ and $\rho_{33} \gg \rho_{22}$ (neglect the pump depletion).

In the time Fourier transform domain, the nonlinear polarization for the probe field is given by the operator $\hat{P}(\omega) = i\kappa\hat{\mathcal{R}}_{23}(\omega)$ with $\kappa = \mathcal{N}_a|D_{23}|^2\omega_p/(2\hbar\varepsilon_0 c)$, where $\mathcal{N}_a$ is atom density. The DC component of $\mathcal{D}(\omega)$ is given by

$$\mathcal{D}(0) = -\left(\frac{\mathrm{Re}[B_0]\mathrm{Im}[C_0] - \mathrm{Im}[B_0]\mathrm{Re}[C_0]}{\mathrm{Re}[B_0]^2 + \mathrm{Im}[B_0]^2}\right) + i\left(\frac{\mathrm{Re}[B_0]\mathrm{Re}[C_0] + \mathrm{Im}[B_0]\mathrm{Im}[C_0]}{\mathrm{Re}[B_0]^2 + \mathrm{Im}[B_0]^2}\right), \tag{2}$$

with $\mathrm{Re}[B_0] = |\Omega_{21}|^2 + \delta_{2ph}\delta + \gamma_{31}\gamma_{23}$, $\mathrm{Im}[B_0] = \delta_{2ph}\gamma_{23} - \delta\gamma_{13}$, $\mathrm{Re}[C_0] = \gamma_{13}\rho_{33} - \gamma_{23}X\rho_{11}$, and $\mathrm{Im}[C_0] = \delta_{2ph}\rho_{33} + \delta\rho_{11}$, where $X = |\Omega_{21}|^2/(\delta^2 + \gamma_{21}^2)$ and $\gamma_{31} = \gamma_{13}$. Since $i\kappa\mathcal{D}(0) = i\kappa\,\mathrm{Re}[\mathcal{D}(0)] - \kappa\,\mathrm{Im}[\mathcal{D}(0)]$, we see that $\mathrm{Im}[\mathcal{D}(0)]$ gives the gain or loss, whereas $\mathrm{Re}[\mathcal{D}(0)]$ gives the phase. Equation (2) has several interesting properties.

1. *Two-Photon Broadband Phase Shifter.* Setting $\kappa\,\mathrm{Im}[\mathcal{D}(0)] = 0$ by making $\mathrm{Re}[C_0]\mathrm{Re}[B_0] + \mathrm{Im}[C_0]\mathrm{Im}[B_0] = 0$ in Eq. (2), we obtain

$$\gamma_{23}\rho_{11}X^2 + \gamma_{13}(\rho_{11} - \rho_{33})X - \gamma_{23}\frac{\delta_{2ph}^2 + \gamma_{13}^2}{\delta^2 + \gamma_{23}^2}\rho_{33} = 0. \tag{3}$$

Clearly, Eq. (3) has no meaningful solution if $\rho_{33} = 0$, signifying the importance of coherently prepared states.

Equation (3) yields a solution for X as a function of δ_{2ph}, which "locks the pump with the two-photon detuning." When this dynamic-locking condition is enforced, we will always have $\mathrm{Im}[\mathcal{D}(0)] = 0$. Consequently, zero gain/loss to the probe field everywhere in the region of interest (i.e., the two-photon detuning δ_{2ph}) can be achieved. This "$|\Omega_P|^2$-δ_{2ph}-locking" is the key operation condition that allows a significant suppression of the atom-light-interaction noise in a gain medium.

In the case where maximum atomic coherence is created prior to the injection of the probe and pump fields, i.e., $\rho_{11} = \rho_{33} = \rho_{31} = 0.5$, Eq. (3) gives

$$X = \frac{|\Omega_{21}|^2}{\delta^2 + \gamma_{23}^2} = \sqrt{\frac{\delta_{2ph}^2 + \gamma_{13}^2}{\delta^2 + \gamma_{23}^2}}. \tag{4}$$

Using $\mathrm{Re}[C_0] = -\mathrm{Im}[C_0]\mathrm{Im}[B_0]/\mathrm{Re}[B_0]$ from the requirement of $\mathrm{Im}[\mathcal{D}(0)] = 0$, we immediately obtain the phase shift per unit propagation distance as $\phi = \kappa\,\mathrm{Re}[\mathcal{D}(0)]$,

$$\phi = -\kappa\frac{\mathrm{Im}[C_0]}{\mathrm{Re}[B_0]} = -\kappa\frac{\delta_{2ph}\rho_{33} + \delta\rho_{11}X}{(\delta^2 + \gamma_{23}^2)X + \delta_{2ph}\delta + \gamma_{23}\gamma_{13}}. \tag{5}$$

Consider the operation condition that $\delta_{2ph}\delta$ dominates the denominator (i.e., $\delta X < \delta_{2ph}$), then Eq. (5) gives $\phi_0 = \kappa\,\mathrm{Re}[\mathcal{D}(0)] \approx -\frac{\kappa}{\delta}\rho_{33}$.

This is a remarkably simple result indicating a typical one-photon transition type of phase shift with a flat zero-gain/loss dispersion, the situation that cannot be achieved with a one-photon process. Since the total imaginary part of the dispersion function decides the gain or loss of the probe light, the condition of $\mathrm{Im}[\mathcal{D}] = 0$ leads to the cancellation of the absorption branch by the gain branch. This results in a zero overall imaginary part and therefore zero gain/loss operation. In addition, since in a typical operation only δ_{2ph} is scanned, thus we have achieved a *constant* phase shift over the entire region of the operation (i.e., insensitive to δ_{2ph} since it does not appear in ϕ_0). Indeed, these features cannot be achieved by any simple three-state EIT scheme or Raman gain scheme alone.

In Fig. 2, we plotted probe-field phase shift and the gain/loss properties as a function of the two-photon detuning. To show a constant π-phase shift with flat zero loss or gain dispersion, we choose the system parameters as $\rho_{11} = \rho_{33} = 0.5$ [29], $\kappa = 2.4 \times 10^9\ \mathrm{s}^{-1}\,\mathrm{cm}^{-1}$ (the corresponding atomic density is about $6 \times 10^{10}\ \mathrm{cm}^{-3}$), $\gamma_{21}/2\pi = 6$ MHz, $\gamma_{23}/2\pi = 6$ MHz, $\gamma_{31}/2\pi = 10$ kHz, $\delta/2\pi = -300$ MHz, $\Omega_{21}/2\pi = 30$ MHz, and $L = 5$ cm. It can be seen that there exists a broad two-photon detuning range [30] in which a π-phase shift with zero gain/loss under the $\Omega_P - \delta_{2ph}$ locking condition Eq. (4). We

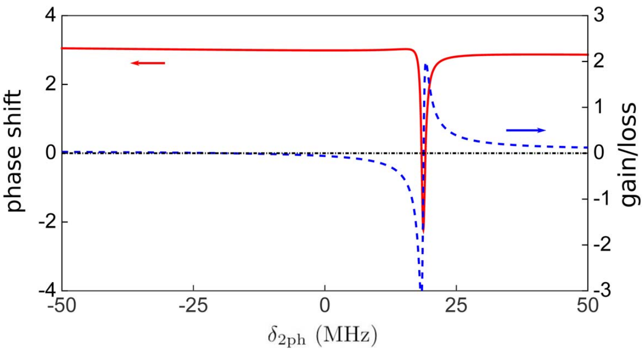

Fig. 2. Probe phase shift $\kappa\,\mathrm{Re}[\mathcal{D}(0)]L$ (red solid line) and the loss/gain $\kappa\,\mathrm{Im}[\mathcal{D}(0)]L$ (blue dashed line) as a function of the two-photon detuning δ_{2ph}. A flat zero gain/loss dispersion with a constant π-phase shift can be achieved by maintaining the locking condition Eq. (4).

point out that this flat zero gain/loss dispersion contributes to very low probe-field phase fluctuation (see Section 4).

2. *Dynamic Optical-Field Attenuator/Amplifier With Zero Phase Shift.* From Eq. (2), taking $\mathrm{Re}[B_0]\mathrm{Im}[C_0]-\mathrm{Im}[B_0]\mathrm{Re}[C_0]=0$, we obtain $\mathrm{Re}[\mathcal{D}(0)]=0$ and

$$\delta\rho_{11}X^2+\delta_{2ph}X+\delta\rho_{33}\frac{\delta_{2ph}^2+\gamma_{13}^2}{\delta^2+\gamma_{23}^2}=0. \tag{6}$$

The dynamic attenuation coefficient is then given by

$$\alpha=\kappa\,\mathrm{Im}[\mathcal{D}(0)]=\kappa\frac{\delta_{2ph}\rho_{33}+\delta\rho_{11}X}{\delta_{2ph}\gamma_{23}-\delta\gamma_{13}}, \tag{7}$$

where X is given by the solution of Eq. (6). Thus, one achieves a phase-insensitive optical-field attenuation or amplification depending on the choice of parameters.

In Fig. 3, we show the probe phase shift and loss/gain dispersion ($\delta/2\pi=-300$ MHz and $\Omega_{21}/2\pi=20$ MHz; other parameters are the same as in Fig. 2). Here, two specific probe-field frequencies, corresponding to two δ_{2ph} at which dynamic probe field absorption and amplification can be achieved with zero phase shift.

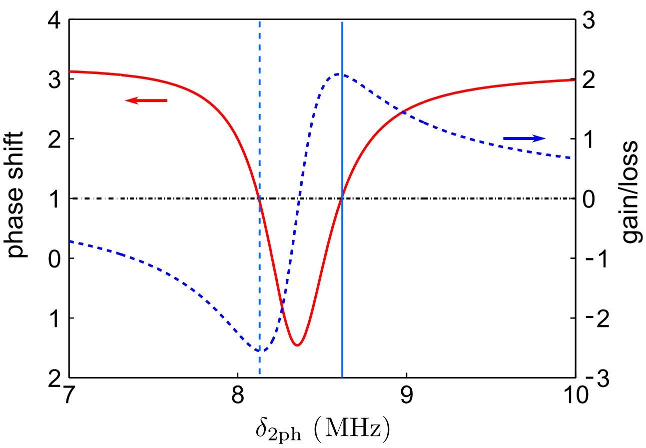

Fig. 3. Probe phase shift $\kappa\,\mathrm{Re}[\mathcal{D}(0)]L$ (red solid line) and the loss/gain $\kappa\,\mathrm{Im}[\mathcal{D}(0)]L$ (blue dashed line) versus the two-photon detuning. The vertical dashed and solid lines indicate significant probe attenuation and amplification without phase change.

3. *Dynamic Probe-Field Transparency.* Probe transparency in a resonant medium relies on EIT configurations in which both one- and two-photon detunings are zero, resulting in the loss of tunability unless a strong pump field is used to create a large transparency window. It is possible, however, to achieve a total transparency with a weak pump in our scheme. It is seen from Eq. (2) that by making $X=|\Omega_{21}|^2/(\delta^2+\gamma_{23}^2)=-\rho_{33}\delta_{2ph}/\rho_{11}\delta$ and $-\delta_{2ph}/\delta=\gamma_{13}/\gamma_{23}$, then $C_0=0$ can be achieved. This is a total transparency without phase shift (see Fig. 4). Clearly, this is possible only when $\rho_{33}\neq 0$.

4. *Low-Noise Probe-Field Phase Shifter.* We now examine the quantum noise characteristics of the probe field when a large phase shift is realized (see Section 1). The Maxwell equation for the probe field Rabi frequency in the slowly varying amplitude and phase approximation is given by

$$\frac{\partial\hat{\Omega}_p}{\partial z}+\frac{1}{c}\frac{\partial\hat{\Omega}_p}{\partial t}=i\kappa\tilde{\rho}_{23}+\frac{D_{23}}{\hbar}\hat{F}(z,t), \tag{8}$$

where the Langevin-like vacuum fluctuation noise operator is given by (define $D_0=(\omega+d_{13})(\omega+d_{23})-|\Omega_{21}|^2$)

$$\hat{F}(z,t)=b_{13}(t)\hat{F}_{13}(z,t)+b_{23}(t)\hat{F}_{23}(z,t), \tag{9}$$

where $b_{13}=\Omega_{21}/D_0$, $b_{23}=-(\omega+d_{13})/D_0$.

Equation (8) can be solved in the time-Fourier-transform domain as a function of the propagation distance z by formal integration without any approximations. This yields a delayed output probe field [28,31,32] as

$$\hat{W}(L,\omega)=\hat{W}(0,\omega)e^{-\Lambda L}+\frac{D_{23}}{\hbar}\int_0^L e^{-\Lambda(L-s)}F(s,\omega)\mathrm{d}s, \tag{10}$$

where $\Lambda=\Lambda(\omega)=-i\kappa\mathcal{D}(\omega)$ and $F(s,\omega)$ is the Fourier transform of Eq. (9). Using Eq. (10) and applying the quantum regression theorem [33,34], the probe-field amplitude noise spectrum in the Fourier domain is

$$S_X(L,\omega)=S_{X1}(L,\omega)+S_{X2}(L,\omega)+S_{X3}(L,\omega), \tag{11}$$

where expressions of $S_{XJ}(L,\omega)$ $(J=1,2,3)$ can be obtained using procedures illustrated in Refs. [28,31,32]. In Eq. (11), $S_{X1}(L,\omega)$ arises from the amplitude noise spectrum of the input probe $S_X(0,\omega)$, $S_{X2}(L,\omega)$ represents the contribution of

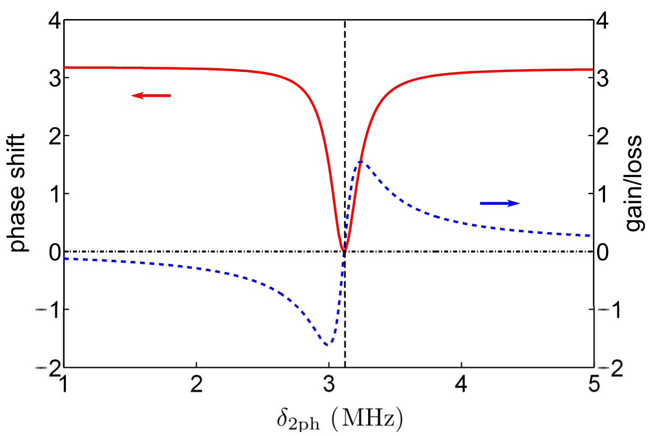

Fig. 4. Probe phase shift $\kappa\,\mathrm{Re}[\mathcal{D}(0)]L$ (red solid line) and the loss/gain $\kappa\,\mathrm{Im}[\mathcal{D}(0)]L$ (blue dashed line) versus the two-photon detuning. The vertical dashed line denotes the two-photon detuning at which a total transparency with zero phase shift can be achieved. Here, $\Omega_{21}/2\pi=12.2$ MHz and other parameters are the same as in Fig. 2.

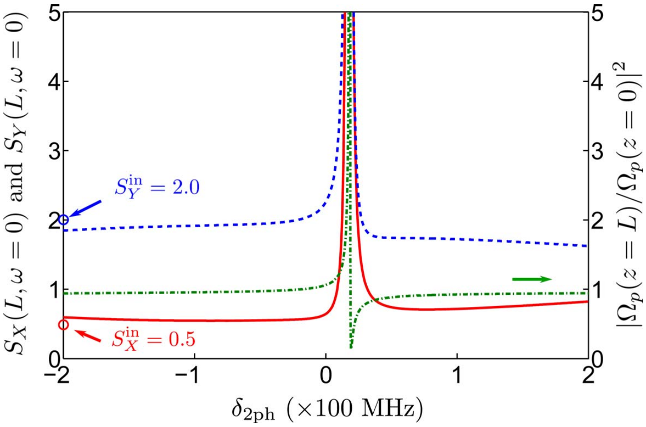

Fig. 5. Plot of amplitude ($S_X(L, \omega = 0)$, blue dashed line) and phase ($S_Y(L, \omega = 0)$, green dotted-dashed line) noise spectra versus δ_{2ph} under the condition of π-phase shift (see Fig. 1). Red solid line: normalized probe field using Eq. (10).

the phase noise spectrum of the input probe $S_Y(0, \omega)$ via the phase-to-amplitude noise conversion [35,36], and $S_{X3}(L, \omega)$ arises from atomic noise due to the random decay process. The probe-field phase noise spectrum can be calculated similarly:

$$S_Y(L, \omega) = S_{Y1}(L, \omega) + S_{Y2}(L, \omega) + S_{Y3}(L, \omega). \quad (12)$$

In Fig. 5, we plot probe amplitude and phase noise spectra versus δ_{2ph} at the exit of the medium. The input field is in a 3 dB squeezed state with quadrature components $S_X(0, \omega) = 0.5$ and $S_Y(0, \omega) = 2$. The probe field acquires negligible additional quantum noise in a broad δ_{2ph} region where zero loss/gain is achieved with a π-phase shift. It is in this broad two-photon detuning region that a high-fidelity, low-noise phase-gate operation may be realized.

In conclusion, we have investigated a novel three-state two-wave mixing scheme with coherently prepared states. The new scheme has many intriguing properties and may operate in several modes as a versatile π-phase shifter or a zero-phase attenuator/amplifier. By locking the pump excitation with the two-photon detuning, a π-phase shifting can be maintained with negligible additional operational quantum noise and also a unit probe fidelity in a broad two-photon detuning range, which are very attractive aspects of the scheme that may lead to the realization of a low-noise phase-gate operation.

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REFERENCES AND NOTES

1. M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information* (Cambridge University, 2000).
2. N. Gisin, G. W. Ribordy, G. Tittel, and H. Zbinden, Rev. Mod. Phys. **74**, 145 (2002).
3. Q. A. Turchette, C. J. Hood, W. Lange, H. Mabuchi, and H. J. Kimble, Phys. Rev. Lett. **75**, 4710 (1995).
4. N. J. Cerf, C. Adami, and P. G. Kwiat, Phys. Rev. A **57**, R1477 (1998).
5. A. Rauschenbeutel, G. Nogues, S. Osnaghi, P. Bertet, M. Brune, J. M. Raimond, and S. Haroche, Phys. Rev. Lett. **83**, 5166 (1999).
6. G. Englert, C. Kurtsiefer, and H. Weinfurter, Phys. Rev. A **63**, 032303 (2001).
7. F. Schmidt-Kaler, H. Häffner, M. Riebe, S. Gulde, G. P. T. Lancaster, T. Deuschle, C. Becher, C. F. Roos, J. Eschner, and R. Blatt, Nature **422**, 408 (2003).
8. S. Gasparoni, J. Pan, P. Walther, P. Rudolph, and A. Zeilinger, Phys. Rev. Lett. **93**, 020504 (2004).
9. J. L. O'Brien, G. J. Pryde, A. G. White, T. C. Ralph, and D. Branning, Nature **426**, 264 (2003).
10. M. Fiorentino and F. N. C. Wong, Phys. Rev. Lett. **93**, 070502 (2004).
11. A. Crespi, R. Ramponi, R. Osellame, L. Sansoni, I. Bongioanni, F. Sciarrino, G. Vallone, and P. Mataloni, Nat. Commun. **2**, 566 (2011).
12. C. Ottaviani, D. Vitali, M. Artoni, F. Cataliotti, and P. Tombesi, Phys. Rev. Lett. **90**, 197902 (2003).
13. M. D. Lukin and A. Imamoglu, Nature **413**, 273 (2001).
14. K. J. Resch, J. S. Lundeen, and A. M. Steinberg, Phys. Rev. Lett. **89**, 037904 (2002).
15. S. Rebić, D. Vitali, C. Ottaviani, P. Tombesi, M. Artoni, F. Cataliotti, and R. Corbalán, Phys. Rev. A **70**, 032317 (2004).
16. C. J. Zhu, L. Deng, and E. W. Hagley, Phys. Rev. A **90**, 063841 (2014).
17. H. S. Kang and Y. F. Zhu, Phys. Rev. Lett. **91**, 093601 (2003).
18. Y. F. Chen, C. Y. Wang, S. H. Wang, and I. A. Yu, Phys. Rev. Lett. **96**, 043603 (2006).
19. R. B. Li, L. Deng, and E. W. Hagley, Phys. Rev. Lett. **110**, 113902 (2013).
20. R. B. Li, L. Deng, and E. W. Hagley, Phys. Rev. A **90**, 063806 (2014).
21. R. B. Li, C. J. Zhu, L. Deng, and E. W. Hagley, Appl. Phys. Lett. **105**, 161103 (2014).
22. J. H. Shapiro, Phys. Rev. A **73**, 062305 (2006).
23. J. Gea-Banacloche, Phys. Rev. A **81**, 043823 (2010).
24. J. Dove, C. Chudzicki, and J. H. Shapiro, Phys. Rev. A **90**, 062314 (2014).
25. K. J. Jiang, L. Deng, and M. G. Payne, Phys. Rev. Lett. **98**, 083604 (2007).
26. L. Deng, M. G. Payne, and W. R. Garrett, Opt. Commun. **242**, 641 (2004).
27. L. Deng, M. G. Payne, and W. R. Garrett, Phys. Rep. **429**, 123 (2006).
28. J. X. Zhang, J. Cai, Y. F. Bai, J. R. Gao, and S. Y. Zhu, Phys. Rev. A **76**, 033814 (2007).
29. A. D. Boozer, R. Miller, T. E. Northup, A. Boca, and H. J. Kimble, Phys. Rev. A **76**, 063401 (2007).
30. Phase deviation from π in a desirable region of δ_{2ph} can also be compensated by adjusting propagation distance.
31. C. P. Lu, C. H. Yuan, and W. P. Zhang, Acta Phys. Sin. **57**, 6976 (2008).
32. C. J. Zhu, Y. Li, L. Deng, E. W. Hagley, and W. R. Garrett, “Propagation characteristics and quantum fluctuation calculation in a coherently-prepared atomic medium,” Opt. Express (submitted).
33. A. Peng, M. Johnsson, W. P. Bowen, P. K. Lam, H. A. Bachor, and J. J. Hope, Phys. Rev. A **71**, 033809 (2005).
34. Y. C. Chen, Y. A. Liao, H. Y. Chiu, J. J. Su, and I. A. Yu, Phys. Rev. A **64**, 053806 (2001).
35. E. S. Polzik, J. Carri, and H. J. Kimble, Phys. Rev. Lett. **68**, 3020 (1992).
36. J. C. Camparo, J. Opt. Soc. Am. B **15**, 1177 (1998).