Controllable time splitting and pulse beating of single-photons with two-component electromagnetically induced transparency

Sheng-Jun Yang,1,2 Xiao-Hui Bao,1,2 and Jian-Wei Pan1,2

1Hefei National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, China
2CAS Center for Excellence and Synergetic Innovation Center in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China

(Dated: January 28, 2015)

Coherent manipulation of single-photon wave packets is essentially important for optical quantum communication and quantum information processing. In this paper, we realize controllable pulse splitting and beating of single-photon wave packets by using a tripod-type EIT medium. The adoption of two control beams enable us to store a single-photon wave packet into superposition of two distinct atomic collective excitations. By controlling the time delay between the two control pulses, we observe splitting of a stored single-photon wave packet into two temporally-distinct modes. By controlling the frequency detuning of the control beams, we observe both temporal beating and frequency-domain beating for the retrieval photon, which verifies the coherence nature of the splitting process and can be utilized as a multi-mode time splitter.

PACS numbers: 42.50.Gy, 42.25.Hz, 42.79.Fm, 03.67.Hk

Techniques for tailoring the dispersion of materials, especially the electromagnetically induced transparency (EIT) method, enable us to control light propagation better than before and inspire lots of applications in quantum optics and atomic physics [1]–[4]. The ordinary EIT structure is three-level atoms interacting with two laser fields, named the signal and control light. By dynamically decreasing/increasing the control light power, coherence state of the signal photon could be transferred into/from the atoms, described as the atom-photon dark-state polaritons [5, 6]. Furthermore, coherent control of the spinor polaritons would lead to numbers of useful quantum state engineering. Particularly, a tripod-type four-level EIT scheme, which categorizes in the state

\[ |\sigma\rangle \]

\[ \tan \theta = \frac{\sqrt{N} g}{|\Omega|}, \]

where \( \tan \theta = \sqrt{N} g/|\Omega| \), \( g = \sqrt{\hbar \omega / 2e_0 V} \), \( N \) is the total atom number, and \( \Omega \) is the Rabi frequency of the control fields, \(|\Omega|^2 = |\Omega_{c1}|^2 + |\Omega_{c2}|^2 \). The atomic component of the polariton has two spinwave excitations \( \hat{\sigma}_{bc1} \) and \( \hat{\sigma}_{bc2} \), where \( \tan \phi = \Omega_{c1}/\Omega_{c2} \), and \( \phi_i \) (\( i = 1, 2 \)) is the

In this paper, by using such a tripod-EIT medium, we experimentally map a signal pulse in the single-photon regime into two atomic spinwave excitations, and demonstrate a time-bin beam splitter for the retrieval signal photon by switching on the two control fields at different time instants. Furthermore by changing the detuning of the control fields, we also observe the waveform beating during the storage and retrieval process. Such phenomena identifies the polariton constructive- and destructive-interference, and could be used to modulate the retrieval waveform of the signal photon. As there’s less than one photon averaged in each signal pulse, the coherent waveform splitting and beating phenomena present here is quantum behavior of individual photons. The controllable time-bin splitting of photons in our system could be useful in quantum information processing based on the dark-state polaritons, especially for the robust time-bin quantum communication architecture [23–25].

As shown in Fig. 1(a), we label the tripod atomic structure with one excited state \( |a\rangle \) and three independent ground states \( |b\rangle, |c_1\rangle \) and \( |c_2\rangle \). All atoms initially locate in the state \( |b\rangle \). A signal quantum field \( \hat{E}_s \) is resonant with the transition \( |b\rangle \rightarrow |a\rangle \), that \( \delta_s = 0 \). Two strong control fields, with the Rabi frequency \( \Omega_{c1} \) and \( \Omega_{c2} \), are related to the transition \( |c_1\rangle \rightarrow |a\rangle \) and \( |c_2\rangle \rightarrow |a\rangle \) respectively. Assuming the single-photon detuning of the control fields \( \delta_{c1} = \delta_{c2} = 0 \), we get the steady eigenstate of the atom-photon polaritons as following [13],

\[ \Psi = \cos \theta \hat{E}_s - \sqrt{N} \sin \theta (\sin \phi e^{-i\phi_1^0} \hat{\sigma}_{bc1} + \cos \phi e^{-i\phi_2^0} \hat{\sigma}_{bc2}), \]

In the tripod-EIT configuration, as shown in Fig. 1(a), three ground atomic levels are coupled with an excited level by two signal fields and one control field [13] or one signal field and two control fields. As there exist a pair of orthogonal dark-state polaritons, whose coherence depends on the amplitude and phase of the control fields, beam splitting of a signal pulse could be achieved based on this tripod-type photon storage [13]. In comparison with other methods [19]–[21], the tripod-EIT scheme highlights the simplicity and high degree of controllability. For instance, in a former experiment that using rapid coherence transport in a wall-coated atomic vapor cell [21], ratio of pulse splitting is rather difficult to control effectively. In addition, the tripod-EIT scheme offers a novel way for the modulation of single-photon wave packets [22].
phase of the control field $\Omega_{c2}$ that transferred onto the atoms. During the EIT storage process, the signal photon is mapped into these two atomic excitations which behave as an atomic qubit and are completely determined by the control fields. As shown in Fig. 2(b), a time-bin superposition state can be generated by successively retrieving the two atomic excitations $\delta_{bc1}$ and $\delta_{bc2}$ at the storage time $t_1$ and $t_2$.

$$|\Phi\rangle_{t_1,t_2} = \sin \phi |1_{t_1} 0_{t_2}\rangle + \cos \phi e^{i \delta \varphi_c} |0_{t_1} 1_{t_2}\rangle,$$

where the relative phase is determined by the two control fields, that $\delta \varphi_c = \varphi_{c1} - \varphi_{c2} + \varphi_0^c - \varphi_0^{c2}$.

In the experiment, the tripod-type system is a $^{87}$Rb cold atomic ensemble loaded by the magnetic optical trapping (MOT). The stray magnetic field is compensated with three orthogonal Helmholtz coils. All the atoms are initially prepared in the degenerate ground state $|5S_{1/2}, F = 1\rangle$, with an optical depth about \(1\)\(3(1)\) corresponding to the D1-line transition $|F = 1\rangle \rightarrow |F' = 1\rangle$. As shown in Fig. 2(a), a right circularly polarized (\(\sigma^+\)) signal photon, with an envelope of $\hat{E}_s$, is resonant of $|F = 1\rangle \rightarrow |F' = 1\rangle$; and two strong control fields, that of left and right circularly polarization (\(\sigma^\mp\)), are resonant or near resonant of $|F = 2\rangle \rightarrow |F' = 1\rangle$, connecting the signal photon with two sub-Zeeman levels of the state $|F = 2\rangle$. Clearly, there exist two independent groups of the tripod-EIT structure, connecting the Raman coherence $|F = 1, m_F = -1\rangle \leftrightarrow |2, -1\rangle \& |2, +1\rangle$ and $|1, 0\rangle \leftrightarrow |2, 0\rangle \& |2, +2\rangle$ respectively. Experiment arrangement of the three light beams is in the same horizontal plane, as shown in Fig. 2(b). The signal beam is sent through the atoms, with a beam diameter $\sim 600 \mu$m, and detected by a single photon detector. Two control fields are forward propagating in a small angle with the signal field, and the beam diameters of them are $\sim 2$ mm, to cover the whole signal beam. The signal and control fields, from two laser diodes, are phase-locked with each other.

First, we verify the time-bin splitting of the signal photons in memory. All the three laser beams are resonant with their relative atomic transition. Time sequence of the experiment is shown in Fig. 2(b). The control fields $\Omega_{c1}$ and $\Omega_{c2}$ are both on to map the signal photon into the atomic excitations. After a storage time $0.5 \mu$s, one control pulse $\Omega_{c1}$ ($\Omega_{c2}$) is switched on, lasting $1 \mu$s to retrieve the corresponding atomic excitations. Subsequently, the second pulse $\Omega_{c2}$ ($\Omega_{c1}$) is on for another $1 \mu$s to retrieve the rest of the atomic excitations. This means that the storage time of the first retrieval component is $0.5 \mu$s and the second $1.5 \mu$s.

As theoretical discussion, beam splitting is related to the control field power. The weight of $\delta_{bc1}$ and $\delta_{bc2}$ in the polariton $\Psi$, depends on the Rabi frequencies $\Omega_{c1}$ and $\Omega_{c2}$. In Fig. 2(a), we show the pulse shapes of the retrieval signal photon for various settings of the control laser power. There are four power settings, that changing the pulse power $\Omega_{c2}$ while keeping $\Omega_{c1}$ constant at $100 \mu$W. As atoms are equally distributed in the ground Zeeman states, if we open $\Omega_{c1}$ first, the storage signal photons caused by different control fields could be retrieved independently in time sequence, as shown in Fig. 2(a). But if we open $\Omega_{c2}$ first, part of the signal photons stored by $\Omega_{c2}$ would be destroyed. This could be avoided if we optically pump all the atoms into a single Zeeman state. From envelope of the wave packet shown, proportion of the signal pulse retrieved by $\Omega_{c1}$ is dropping while increasing the laser power $\Omega_{c2}$. In order to see clearly the beam splitting effect, we also calculate the retrieval proportions $\eta$ for different control power settings in Fig. 2(b). The grey dashed line corresponds to the ideal situation that storage efficiency of the signal photon induced by the two control fields are the same. Because the signal pulse group velocity $v_g \propto |\Omega|^2$, the EIT storage efficiency decreases while increasing the control light power. Thus for large control power of $\Omega_{c2}$, the proportion $\eta$ is below the value of $|\Omega_{c2}/\Omega_{c1}|^2$.

By tuning the relative Rabi frequency of the control...
pulses, we have successfully split the signal photon into two parts that propagating in the same direction at controllable storage time. The two splitting components are coherent correlated as the signal photon is simultaneously stored in the two spinwave excitations. In the following, we will study such polariton interference by changing the control field detuning. For the tripod-EIT configuration, there exists another orthogonal spinor polariton,

$$\Psi^\perp = \sqrt{N} (\cos \phi e^{-i\phi_0} \hat{\sigma}_{1c} - \sin \phi e^{-i\phi_0} \hat{\sigma}_{2c}), \quad (3)$$

which doesn’t interact with the signal photon $\hat{E}_s$ and $\langle \Psi^\perp | \Psi \rangle = 0$. If we change the amplitude and phase of the two control fields, the polaritons $\Psi$ and $\Psi^\perp$ would be transformed, similar to the optical waveplate rotation. Only the component that in phase with the retrieval control field setting could be released out of the atomic medium; and the rest would keep as stationary atomic excitation during the retrieval process. Thus we could also achieve beam splitting by tuning the relative phase of the two control fields. Assuming the power of the two control fields keep constant during the storage and retrieval process, but the frequency detuning is different, that $\delta_{c1} - \delta_{c2} = 2\delta_c$, $\delta_{c1} + \delta_{c2} = 2\delta_s$, evolution of the two spinwave excitations satisfies

$$-i \frac{\partial \Psi}{\partial t} = (\delta_s - \delta_c \cos 2\phi) \Psi + \delta_c \sin 2\phi \Psi^\perp. \quad (4)$$

Clearly, if $\delta_s = 0$, $\delta_c \neq 0$ and $|\Omega_{c1}| = |\Omega_{c2}|$, the two atomic excitations alternately evolve into each other, and would create a period destructed and -constructed interference beating signals with an oscillating period of $2\pi/\delta_c$.

Here in order to identify such polariton interference, the two control fields are set in opposite frequency detuning, that $\delta_{c1} = -\delta_{c2} = \delta_c$. As $\{\delta_{c1}, \delta_{c2}\} \neq 0$, the storage efficiency would become smaller than that of resonance. But when the detuning is small, the beating period is large compared with the retrieval pulse width and no obvious beating signals are observable in such situation. Considering these two factors, we choose the detuning $\delta_c$ of 2MHz and both the control laser with power of $\sim 100 \mu W$. The control fields are simultaneously on during the storage and retrieval process. And we observe the polariton interference in both process. The waveform beating of the retrieval signal pulse is shown in Fig. 3(a) for different storage time $0.2 - 0.8 \mu s$. The retrieval signal field exhibits series of maxima and minima intensity oscillation due to the polariton interference, and the beating period is about $250\,\text{ns}$. Because the stationary atomic excitations and the retrieval control field would accumulate a phase difference $\delta_c T$ during a storage time $T$, pulse shape of the retrieval signal at $\tau \mu s$ and $(\tau + 0.25n) \mu s$ ($n=1, 2, 3, \ldots$) are similar. This shows that the stored phase information and coherence is preserved in the atomic medium. By fine adjustment of the control fields, the beating signals would be more obvious, and the destructive points could reach zero. Such waveform interference may allow us to retrieve a sequence of Gaussian-like wave pulses with the same pulse width, more than just two pulse splitting discussed above.

For certain storage time $T$, the phase shift $\delta_c T$ varies with the control field detuning $\delta_c$. So at the beginning of the retrieval process, the starting in-phase component of the spinwave excitations periodically oscillates for different detuning $\delta_c$, and the beating process would start at different retrieval pulse amplitude. In Fig. 3(b), we record the initial 200 ns retrieval signal photon counts after a storage time $1 \mu s$ and $5 \mu s$ by sweeping $\delta_c$ from 0 MHz to 2 MHz. The retrieval photon counts are oscillating with the control field detuning, with a frequency oscillating period $1/2T$. The retrieval photon counts are not the maximum at the resonant condition $\delta_c = 0$ MHz, because the different AOM (acousto-optic modulator).
Figure 4. (color online). (a) Interference beating of the signal waveforms for different storage time (0.2 – 0.8 \(\mu\)s), where the control field detuning \(\delta_1 = -\delta_{c2} = 2.0\) MHz, result of an oscillation period 0.25 \(\mu\)s. (b) Retrieval signal photon counts for different control field detuning \(\delta_c\) at the storage time of 1 \(\mu\)s (black square) and 5 \(\mu\)s (red circle). Sum duration of the signal photon counts \(n\) is the initial 200 ns of the retrieved signal pulse.

switching time of the two control light would generate an additional phase shift \(\delta \phi_c \sim 0.78\pi\). For long coherence lifetime, we could obtain much high resolution of the frequency difference \(\delta_c\), which may be useful in precise frequency measurement and metrology.

In conclusion, we have experimentally studied the propagation and storage of individual photons in a tripod-type EIT medium. We achieved time-bin splitting of a signal photon that is stored in two atomic spinwave excitations. The splitting ratio and time separation is highly controllable. By tuning the frequency of the two control fields, we have further observed both temporal beating and frequency-domain beating for the retrieval signal photon. To the best of our knowledge, this should be the first time of observing the tripod-type polariton interference in the single-photon regime. By improvement of the storage efficiency \([27 [28]\), much better experimental results will be achievable in the near future. Furthermore, with similar methods it is also possible to realize a pulse combiner for single-photon qubits. Such kind of controllable manipulation of single-photon temporal modes in tripod-EIT medium will have potential applications in the time-bin based quantum communication architecture \([23 [24]\), which is advantageous in long-distance quantum state transfer.

This work was supported by the National Natural Science Foundation of China, National Fundamental Research Program of China (under Grant No. 2011CB921300), and the Chinese Academy of Sciences. X.-H.B. acknowledges support from the Youth Qianren Program.

Note added.—After completing this work we became aware of a related experiment with a double-tripod spinor system by Lee et al. \([29]\).

\[\]

[1] M. D. Lukin, Rev. Mod. Phys. 75, 457 (2003)
[2] M. Fleischhauer, A. Imamoglu, and J. Marangos, Rev. Mod. Phys. 77, 633 (2005)
[3] M. Fleischhauer and M. D. Lukin, Phys. Rev. Lett. 84, 5094 (2000)
[4] M. Fleischhauer and M. D. Lukin, Phys. Rev. A 65, 022314 (2002)
[5] N. Sangouard, C. Simon, H. de Riedmatten, and N. Gisin, Rev. Mod. Phys. 83, 33 (2011)
[6] J.-W. Pan, Z.-B. Chen, C.-Y. Lu, H. Weinfurter, A. Zeilinger, and M. Zukowski, Rev. Mod. Phys. 84, 777 (2012)
[7] E. Paspalakis, J. Opt. B 4, S372 (2002)
[8] D. Petrosyan and Y. P. Malakyan, Phys. Rev. A 70, 023822 (2004)
[9] S. Rebić, D. Vitali, C. Ottaviani, P. Tombesi, M. Artoni, F. Cataliotti, and R. Corbalán, Phys. Rev. A 70, 032317 (2004)
[10] I. E. Mazets, Phys. Rev. A 71, 023806 (2005)
[11] J.-H. Wu, A.-J. Li, Y. Ding, Y.-C. Zhao, and J.-Y. Gao, Phys. Rev. A 72, 023802 (2005)
[12] A. Raczyński, M. Rzepecka, J. Zaremba, and S. Zielińska-Kaniasty, Opt. Commun. 260, 73 (2006)
[13] A. Raczyński, J. Zaremba, and S. Zielińska-Kaniasty, Phys. Rev. A 75, 013810 (2007)
[14] Y. Han, J. Xiao, Y. Liu, C. Zhang, H. Wang, M. Xiao, and K. Peng, Phys. Rev. A 77, 023824 (2008)
[15] L. Karpa, F. Wieweger, and M. Weitz, Phys. Rev. Lett. 101, 170406 (2008)
[16] S. Li, X. Yang, X. Cao, C. Zhang, C. Xie, and H. Wang, Phys. Rev. Lett. 101, 073602 (2008)
[17] H. Wang, S. Li, Z. Xu, X. Zhao, L. Zhang, J. Li, Y. Wu, C. Xie, K. Peng, and M. Xiao, Phys. Rev. A 83, 043815 (2011)
[18] K. Słowik, A. Raczyński, J. Zaremba, and S. Zielińska-Kaniasty, Opt. Commun. 285, 2392 (2012)
[19] T. Wang, M. Kostrum, and S. F. Yelin, Phys. Rev. A 70, 053822 (2004)
[20] Y. Xiao, M. Klein, M. Hohensee, L. Jiang, D. F. Phillips, M. D. Lukin, and R. L. Walsworth, Phys. Rev. Lett. 101, 043601 (2008)
[21] M. Hosseini, B. M. Sparkes, G. Hétet, J. J. Longdell, P. K. Lam, and B. C. Buchler, Nature 461, 241 (2009)
[22] Q.-Q. Bao, J.-W. Gao, C.-L. Cui, G. Wang, Y. Xue, and J.-H. Wu, Opt. Express 19, 11832 (2011)
[23] J. Brendel, N. Gisin, W. Tittel, and H. Zbinden, Phys.
[24] W. Tittel, J. Brendel, H. Zbinden, and N. Gisin, \textit{Phys. Rev. Lett.} \textbf{84}, 4737 (2000).

[25] K. Inoue, E. Waks, and Y. Yamamoto, \textit{Phys. Rev. Lett.} \textbf{89}, 037902 (2002).

[26] Y.-H. Chen, M.-J. Lee, I.-C. Wang, S. Du, Y.-F. Chen, Y.-C. Chen, and I. A. Yu, \textit{Phys. Rev. Lett.} \textbf{110}, 083601 (2013).

[27] U. Schnorrberger, J. D. Thompson, S. Trotzky, R. Pugatch, N. Davidson, S. Kuhr, and I. Bloch, \textit{Phys. Rev. Lett.} \textbf{103}, 033003 (2009).

[28] Y. O. Dudin, R. Zhao, T. A. B. Kennedy, and A. Kuzmich, \textit{Phys. Rev. A} \textbf{81}, 041805 (2010).

[29] M.-J. Lee, J. Ruseckas, C.-Y. Lee, V. Kudri\v{s}ov, K.-F. Chang, H.-W. Cho, G. Juzeli\u{n}as, and I. Yu, \textit{Nature Commun.} \textbf{5}, 5542 (2014).