Bichromatic field generation from double-four-wave mixing in a double-electromagnetically induced transparency system

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Abstract. We demonstrate double electromagnetically induced transparency (double-EIT) and double four-wave mixing (double-FWM) based on a new scheme of non-degenerate four-wave mixing (FWM) involving five levels of a cold $^{85}$Rb atomic ensemble, in which the double-EIT windows are used to transmit the probe field and enhance the third-order nonlinear susceptibility. The phase-matching conditions for both four-wave mixings can be satisfied simultaneously. The frequency of one component of the generated bichromatic field is less than the other by ground-state hyperfine splitting (3 GHz). This specially designed experimental scheme for simultaneously generating different nonlinear wave-mixing processes is expected to find applications in quantum information processing and cross-phase modulation. Our results agree well with the theoretical simulation.

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Electromagnetically induced transparency (EIT) is a quantum interference phenomenon that allows for the transmission of light through an otherwise opaque atomic medium [1]. The importance of EIT stems from the fact that it results in a greatly enhanced linear and nonlinear susceptibility in the medium near the induced transparent frequency window and is associated with steep dispersion. So EIT is widely used in light slowing and light storage [8–11], biphoto wave packet generation and modulation in cold atoms [12–15], cross-phase modulation [16–19] and so on. Under EIT conditions, the four-wave mixing (FWM) process can be resonantly enhanced [4–7], and two or more wave-mixing processes (e.g. FWM and six-wave mixing) can coexist and interfere with each other [21, 22]. In [23], the authors realized the simultaneous control of two four-wave-mixing fields by changing the atomic density, the intensity and the detuning of the coupling field in a triple-Λ-type atomic system in a hot $^{85}$Rb cell. In their recent work [24], they also successfully observed the generation of four and six strongly correlated and anticorrelated laser fields from such a system.

The bichromatic EIT in cold atoms has been experimentally studied [28], in which multiple-peaked probe absorption spectra under bichromatic coupling fields have been observed. The FWM signal with multi-peak structure in such a system has been performed [29]. Bichromatic optical solitons could be generated in a cold atomic cloud in the condition of a pulsed probe field and a pulsed FWM field of considerably different frequency [30, 31]. In this paper, we report a new experimental study of the double FWM in a five-level atomic system. Two phase-matching conditions of FWM could be satisfied simultaneously and the two generated FWM signals are observed. As compared to similar work in [23, 24], our work shows that such an experimental scheme could generate a so-called bichromatic field. That is, the two generated FWM signals not only have controllable relative strength, but also the same spatial and temporal mode and polarization. Such a special third-order nonlinear wave mixing may have potential applications in quantum information processing and cross-phase modulation at low light level.

2. Theoretical model

Figure 1 shows the scheme of our experiment. States $|1\rangle$ and $|3\rangle$ are the degenerate Zeeman sublevels corresponding, respectively, to the magnetic quantum numbers $m_F = -3$ and $m_F = -1$ of the ground-state hyperfine level $F = 3$ of $^{85}$Rb. The state $|2\rangle$ corresponds to the other hyperfine level $|5/2S_{1/2}F = 2, m_F = -1\rangle$. And $|4\rangle$ and $|5\rangle$ are the excited states: $|5/2P_{1/2}F = 3, m_F = -2\rangle$ and $|5/2P_{3/2}F = 3, m_F = -3\rangle$, respectively. The coupling field $\omega_{c1}$ with a frequency detuning $\Delta_1$ couples the transition $|2\rangle \rightarrow |4\rangle$, and similarly the coupling field $\omega_{c2}$ with a detuning $\Delta_2$ couples the transition $|3\rangle \rightarrow |4\rangle$. The two coupling beams are spatially mode matched by coupling them into the same single-mode fiber and collimated to a beam diameter of 3.2 mm in the vacuum chamber. Both of the two coupling beams are $\sigma^-$ polarized. The pump laser $\omega_p$ is $\sigma^+$ polarized and red-detuned $\Delta_p$ from the transition $|1\rangle \rightarrow |5\rangle$. The probe field $\omega_s$ has the same frequency but opposite circular polarization to the coupling beam $\omega_{c2}$. The presence of the pump beam, two coupling beams and the probe beam will construct two possible FWM paths ($|3\rangle \rightarrow |4\rangle \rightarrow |1\rangle \rightarrow |5\rangle \rightarrow |3\rangle$ and $|2\rangle \rightarrow |4\rangle \rightarrow |1\rangle \rightarrow |5\rangle \rightarrow |2\rangle$). There are two possible phase-matching conditions $\vec{k}_p + \vec{k}_{c1} + \vec{k}_s + \vec{k}_{as1} = 0$ and $\vec{k}_p + \vec{k}_{c2} + \vec{k}_s + \vec{k}_{as2} = 0$, where $\vec{k}_{as1}$
\[ H_{\text{int}} = \hbar (\Delta_p |5\rangle \langle 5| - (\Delta_1 - \Delta_s) |2\rangle \langle 2| + \Delta_s |3\rangle \langle 3| + \Delta_s |4\rangle \langle 4|) - \hbar (\Omega_p |5\rangle \langle 1| + \Omega'_{as1} |5\rangle \langle 2| + \Omega'_{as2} |5\rangle \langle 3| + \Omega_s |4\rangle \langle 1| + \Omega_c1 |4\rangle \langle 2| + \Omega_c2 |4\rangle \langle 3| + \text{H.c.}) , \]

where \( \Omega_i \) is the Rabi frequency of beam \( i \), \( \Omega'_{as1} = \Omega_{as1} \exp[i(\Delta_1 - \Delta_s)t] \) and \( \Omega'_{as2} = \Omega_{as2} \exp[i\Delta_st] \) (which come from the rotating wave approximation). The master equation for the atomic density operator will determine the dynamics of the laser-driven atomic system:

\[
\frac{d\rho}{dt} = \frac{1}{i\hbar} [H_{\text{int}}, \rho] + \sum_{m=1,2,3} \frac{\Gamma_{4m}}{2} [2\hat{\sigma}_{m4} \rho \hat{\sigma}_{4m} - \hat{\sigma}_{4m} \rho - \rho \hat{\sigma}_{4m}] + \sum_{n=1,2,3} \frac{\Gamma_{5n}}{2} [2\hat{\sigma}_{n5} \rho \hat{\sigma}_{5n} - \hat{\sigma}_{5n} \rho - \rho \hat{\sigma}_{5n}]
\]

\[
+ \sum_{i=2,3,4,5} \frac{\gamma_{i\text{deph}}}{2} [2\hat{\sigma}_{ii} \rho \hat{\sigma}_{ii} - \hat{\sigma}_{ii} \rho - \rho \hat{\sigma}_{ii}],
\]

where \( \Gamma_{4m} \) and \( \Gamma_{5n} \) are the spontaneous emission rates out of states \(|4\rangle \) and \(|5\rangle \) to states \(|m\rangle \) and \(|n\rangle \) \((m, n = 1, 2, 3)\), respectively. The \( \gamma_{\text{deph}} \) is the dephasing rate of state \(|i\rangle \) \((i = 2, 3, 4, 5)\), \( \rho \) is the density matrix and \( \sigma_{ij} \) is the projection operator. For convenience, we define the total decay rate out of states \(|4\rangle \) and \(|5\rangle \) as \( \Gamma_4 = \Gamma_{41} + \Gamma_{42} + \Gamma_{43} \), \( \Gamma_5 = \Gamma_{51} + \Gamma_{52} + \Gamma_{53} \), respectively. The coherence decay rates of these states are defined as \( \gamma_{21} = \gamma_{2\text{deph}} \), \( \gamma_{31} = \gamma_{3\text{deph}} \), \( \gamma_{32} = \gamma_{2\text{deph}} + \gamma_{3\text{deph}} \), \( \gamma_{41} = \Gamma_4 + \gamma_{4\text{deph}} \), \( \gamma_{42} = \Gamma_4 + \gamma_{4\text{deph}} + \gamma_{2\text{deph}} \), \( \gamma_{43} = \Gamma_4 + \gamma_{4\text{deph}} + \gamma_{3\text{deph}} \), \( \gamma_{51} = \Gamma_5 + \gamma_{5\text{deph}} \), \( \gamma_{52} = \Gamma_5 + \gamma_{5\text{deph}} + \gamma_{2\text{deph}} \) and \( \gamma_{53} = \Gamma_5 + \gamma_{5\text{deph}} + \gamma_{3\text{deph}} \). From equations (1) and (2),
we derive the following optical Bloch equations for the off-diagonal density matrix elements in the steady-state condition:

\[
\begin{align*}
\left[ -\frac{\gamma_{21}}{2} - (\Delta_1 - \Delta_s) \right] \rho_{21} - \frac{\Omega_p}{2} \rho_{25} + \frac{\Omega_{c1}}{2} \rho_{41} - \frac{\Omega_s}{2} \rho_{24} + \frac{\Omega_{as1}}{2} \rho_{51} &= 0 \\
\left( -\frac{\gamma_{31}}{2} + \Delta_s \right) \rho_{31} - \frac{\Omega_p}{2} \rho_{35} + \frac{\Omega_{c2}}{2} \rho_{41} - \frac{\Omega_s}{2} \rho_{34} + \frac{\Omega_{as2}}{2} \rho_{51} &= 0 \\
\left( -\frac{\gamma_{22}}{2} + \Delta_1 \right) \rho_{32} + \frac{\Omega_{c1}}{2} \rho_{21} + \frac{\Omega_{c2}}{2} \rho_{31} + \frac{\Omega_s}{2} \rho_{11} &= 0 \\
\left( -\frac{\gamma_{41}}{2} + \Delta_s \right) \rho_{41} + \frac{\Omega_{c1}}{2} \rho_{21} + \frac{\Omega_{c2}}{2} \rho_{31} + \frac{\Omega_s}{2} \rho_{11} &= 0 \\
\left( -\frac{\gamma_{42}}{2} + \Delta_1 \right) \rho_{42} + \frac{\Omega_{c1}}{2} \rho_{22} + \frac{\Omega_{c2}}{2} \rho_{32} + \frac{\Omega_s}{2} \rho_{12} &= 0 \\
\left( -\frac{\gamma_{43}}{2} \right) \rho_{42} + \frac{\Omega_{c1}}{2} \rho_{23} + \frac{\Omega_{c2}}{2} \rho_{33} + \frac{\Omega_s}{2} \rho_{13} &= 0 \\
\left( -\frac{\gamma_{51}}{2} + \Delta_p \right) \rho_{51} + \frac{\Omega_p}{2} \rho_{11} + \frac{\Omega_{as1}}{2} \rho_{21} + \frac{\Omega_{as2}}{2} \rho_{31} &= 0 \\
\left[ -\frac{\gamma_{52}}{2} + (\Delta_p + \Delta_1 - \Delta_s) \right] \rho_{52} + \frac{\Omega_p}{2} \rho_{12} + \frac{\Omega_{as1}}{2} \rho_{22} + \frac{\Omega_{as2}}{2} \rho_{32} &= 0 \\
\left[ -\frac{\gamma_{53}}{2} + (\Delta_p - \Delta_s) \right] \rho_{53} + \frac{\Omega_p}{2} \rho_{13} + \frac{\Omega_{as1}}{2} \rho_{23} + \frac{\Omega_{as2}}{2} \rho_{33} &= 0 \\
\frac{\Omega_p}{2} \rho_{14} + \frac{\Omega_{as1}}{2} \rho_{24} + \frac{\Omega_{as2}}{2} \rho_{34} - \frac{\Omega_s}{2} \rho_{51} - \frac{\Omega_{c1}}{2} \rho_{52} - \frac{\Omega_{c2}}{2} \rho_{53} &= 0.
\end{align*}
\]

In equations (3)–(12), we have assumed that \( \rho_{54} = 0 \). We consider the zeroth-order perturbation expansion with the assumption of \( \Omega_{c1}, \Omega_{c2}, \Omega_p \gg \Omega_s, \Omega_{as1}, \Omega_{as2} \) (our experimental conditions) and the initial atomic distribution in the ground state \( |1\rangle \) (\( \rho_{11} = 1, \rho_{22} = 0, \rho_{33} = 0, \rho_{44} = 0, \rho_{55} = 0, \) the initial state preparation), and derive the steady-state solutions to the above equations [12, 26, 27]. After some calculations, we obtain the first and third order nonlinear
susceptibilities of this system, describing the generation of anti-Stokes fields $\omega_{as1}$ and $\omega_{as2}$, respectively.

$$\rho^{(1)}_{s2} = \frac{i\Omega_{as1}[\gamma_{21} + 2i(\Delta_1 - \Delta_s)]}{3\{-\gamma_{s2} - 2i(\Delta_1 + \Delta_p - \Delta_s)][\gamma_{21} + 2i(\Delta_1 - \Delta_s)] + |\Omega_p|^2\}$$ \hspace{1cm} (13)

$$\rho^{(1)}_{s3} = \frac{i\Omega_{as2}[\gamma_{s1} - 2i\Delta_s]}{3\{[\gamma_{s3} + 2i(\Delta_p - \Delta_s)][\gamma_{s1} - 2i\Delta_s] + |\Omega_p|^2\}$$ \hspace{1cm} (14)

$$\rho^{(3)}_{s2} = \frac{i\Omega_{c1}(\gamma_{s2} - 2i\Delta_1)\gamma_{43}\Omega_p\Omega^*_p}{3\{[\gamma_{42} + 2i\Delta_1)(\gamma_{s2}\gamma_{43} - 2i\gamma_{43}\Delta_1 + |\Omega_{c1}|^2] + \gamma_{43}|\Omega_{c1}|^2\} \times \{-\gamma_{21} - 2i(\Delta_1 - \Delta_s)[\gamma_{s2} + 2i(\Delta_1 + \Delta_p - \Delta_s)] + |\Omega_p|^2\}$$ \hspace{1cm} (15)

$$\rho^{(3)}_{s3} = \frac{(\gamma_{s2} + 2i\Delta_1)(i\gamma_{42} + 2\Delta_1)\gamma_{c2}\gamma_{43}\Omega^*_p\Omega_p}{3\{[\gamma_{42} - 2i\Delta_1)(\gamma_{s2}\gamma_{43} + 2i\gamma_{43}\Delta_1 + |\Omega_{c1}|^2] + \gamma_{43}|\Omega_{c1}|^2\} \times \{[\gamma_{s3} + 2i(\Delta_p - \Delta_s)](\gamma_{s1} - 2i\Delta_s) + |\Omega_p|^2\}$$ \hspace{1cm} (16)

The polarization in the atomic medium generated by the applied field is defined as $P = Nu\rho$ (where $N$ is the density of atoms and $u$ is the dipole moment). Polarization serves as the source term in Maxwell’s equations and determines the electromagnetic field dynamics. In our system, the powers of the generated anti-Stokes fields ($\omega_{as1}$ and $\omega_{as2}$) are very small with respect to the pump field. The amplitude of the FWM signal fields we calculated are proportional to the third-order nonlinear susceptibilities $\rho^{(3)}_{s2}$ and $\rho^{(3)}_{s3}$. We could use these expressions to simulate our experimental results.

3. Experimental setup and results

We now turn to the experimental part of this paper. A two-dimensional magneto-optical trap of $^{85}$Rb with a maximal optical depth (OD) of 38 is employed in this experiment [25]. We use an amplified external cavity diode laser (ECDL) (TA100, 780 nm, Toptica) as the cooling beams and another ECDL (DL100, 780 nm, Toptica) as the repumper. The TA100 has an output power of 430 mW, locked to 15 MHz to the red of the $5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F = 4)$ transition. After beam modulating and single-mode fiber filtering, we have 100 mW cooling power available in the vacuum chamber. The repumper with an available power of 25 mW is locked resonantly to the $5S_{1/2}(F = 2) \rightarrow 5P_{3/2}(F = 2)$ transition.

All the four beams are collimated as figure 2 so as to satisfy the phase-matching conditions simultaneously. The probe beam ($\omega_p$) injects along the long axis of the cigar-shaped atomic cloud and is focused on the center of the cloud. The pump beam ($\omega_p$) with $\sigma+$ polarization counter propagates with the two coupling beams ($\omega_{as1}$ and $\omega_{as2}$, $\sigma-$ polarized) and all the three beams overlap the cigar-shaped atomic cloud. The coupling-pump axis (coupling and pump beams) has an angle of 2 degrees from the Stokes–anti-Stokes axis (probe beam and FWM signals). All the lasers used in the experiment are provided by three commercial ECDLs (DL100, Toptica), and pass through the respective acousto-optic modulators (AOMs) for beam switching and frequency shifting. The transmission spectrum of the probe beam is detected by a photomultiplier tube PMT1 (H10721, Hamamatsu). And we use PMT2 to detect the generated FWM signals ($\omega_{as1}$ and $\omega_{as2}$).
Figure 2. Experimental configuration for the double-EIT and double-FWM. The angle between the Stokes–anti-Stokes axis and the coupling-pump axis is 2°. This angle can filter noise from the pump and coupling beams. The Stokes beam is focused on the center of the atom cloud, and pump and coupling beams are collimated so as to totally overlap the Stokes beam in the cloud.

Figure 3. Observation of double-EIT versus probe detuning. The widths of the two transparent windows are different because of the different Rabi frequencies of coupling beams $\omega_{c1}$ and $\omega_{c2}$. The coupling beam $\omega_{c1}$ is locked 5 MHz to the red of the respective transition, and we tune the detuning of $\omega_{c2}$ ($-5$ MHz in (a) and $-3$ MHz in (b)). The two coupling beams have the same detuning in (c).

The atoms are initially prepared on the state $|5S_{1/2}, F = 3, m_F = -3\rangle$. By turning off the MOT trapping laser while keeping the repumper on for 200 $\mu$s, the atoms are prepared at the ground level $|1\rangle$, as shown in figure 1. The experiment is performed in a 700 $\mu$s window after shutting off the trapping and repumping beams. The whole process repeats every 33 ms. We lock the coupling beams $\omega_{c1}$ and $\omega_{c2}$ in different frequency detunings near the respective transitions and scan the probe field frequency in the detuning range of $-40$–$40$ MHz near the $|5S_{1/2}, F = 3\rangle \rightarrow |5P_{1/2}, F = 3\rangle$ transition. Here, the pump beam is blocked. The two coupling beams ($\omega_{c1}$ and $\omega_{c2}$) will create transparent windows simultaneously for the probe field ($\omega_s$) (see figure 1). Depending on the frequency detunings of the two coupling beams, these two EIT windows can either overlap or be separated in frequency on the probe beam transmission signal (as shown in figure 3). We could find the two transparent windows for the probe field in the three curves of figure 3.
Figure 4. Observation of double peaks in the FWM spectrum versus the probe frequency detuning under different coupling frequency detunings. The experimental results (blue dot) fit well with the theoretical simulation (red line). The simulating parameters are: $\gamma = 2\pi \times 6$ MHz, $\Omega_s = 2\gamma$, $\Delta_p = 25\gamma$, $\Delta_s = 0$, $\Omega_{c1} = 3.6\gamma$, $\Omega_{c2} = 2.4\gamma$, $\Omega_p = 4.0\gamma$, $\gamma_{2\text{deph}} = 0.02\gamma$, $\gamma_{3\text{deph}} = 0.008\gamma$, OD = 38.

We then inject a pump beam on the atomic cloud and build up the FWM configuration. There are two possible phase matching conditions $\vec{k}_p + \vec{k}_{c1} + \vec{k}_s + \vec{k}_{as1} = 0$ and $\vec{k}_p + \vec{k}_{c2} + \vec{k}_s + \vec{k}_{as2} = 0$. The simultaneously opened double-EIT windows in this five-level atomic system allow the observation of these two nonlinear optical processes at the same time; both of the two phase-matching conditions could be satisfied simultaneously. The results are shown in figure 4.

By individually controlling (or tuning) the EIT windows, the generated two FWM signals can be clearly separated and distinguished or pulled together (by adjusting the coupling frequency detunings). The two anti-Stokes fields generated have the frequencies of $\omega_{as1} = \omega_p + \omega_{c1} - \omega_s$ and $\omega_{as2} = \omega_p + \omega_{c2} - \omega_s$, respectively. We tune the frequency detuning of the coupling beam $\omega_{c1}$ from $-21.5$ MHz to $16$ MHz and lock the coupling beam $\omega_{c2}$ resonant with the respective transition. We then similarly scan the probe frequency. It is found that not only will the transparent windows for the probe field follow the coupling beam ($\omega_{c1}$) detuning, but so will the generated anti-Stokes field $\omega_{as1}$. The pump beam will induce transparent windows for both the anti-Stokes fields because of the EIT effect. The full-widths at half-maximum (FWHM) of the two FWM peaks, which were measured to be 6.7 MHz for $\omega_{as1}$ and 2.3 MHz for $\omega_{as2}$, are determined by the Rabi frequencies of the pump and respective coupling beams.

We could see from figure 4 that two different types of FWM processes could be realized simultaneously, which means that phase matching and energy conservation could be satisfied for
both the processes in this experimental configuration. As shown in figure 4(c), if the coupling beams $\omega_{c1}$ and $\omega_{c2}$ have the same frequency detuning to the respective transitions, the generated anti-Stokes signals will overlap with a frequency difference that is equal to the ground-state hyperfine splitting (3 GHz). Thus a bichromatic field could be carried out from this five-level system. It is indicated in figure 4 that the theoretical red curves in the four panels, which come from the third-order nonlinear susceptibilities $\rho_5^{(3)}$ and $\rho_6^{(3)}$, agree well with the experimental data lines (blue). In our system, the powers of the generated anti-Stokes fields ($\omega_{as1}$, $\omega_{as2}$) are very small with respect to the pump and coupling fields. So we can ignore the linear susceptibilities. The parameters used in the simulation are: $\gamma = 2\pi \times 6$ MHz, $\Omega_s = 2\gamma$, $\Delta_p = 25\gamma$, $\Delta_s = 0$, $\Omega_{c1} = 3.6\gamma$, $\Omega_{c2} = 2.4\gamma$, $\Omega_p = 4.0\gamma$, $\gamma_{2\text{deph}} = 0.02\gamma$, $\gamma_{3\text{deph}} = 0.008\gamma$, OD = 38.

4. Conclusion

In conclusion, we have experimentally demonstrated and theoretically modeled bichromatic field generation from a double-FWM system. The theoretical simulation agrees well with the experimental results (see figure 4). The bichromatic field generated from the two FWM processes is a potential candidate for color-entanglement and cross-phase modulation. The two colors in the bichromatic field could have the same polarization, intensity and spatial mode, except for the color. Such a coexistence of two FWM processes allows us to investigate the interplay between these two nonlinear optical effects. If we assume that the light–atom interaction time is short or the intensities of the coupling and pump fields are weak, both the mean photon numbers in the two generated FWM pulses are much smaller than 1. Thus the photon state at the low light level could be seen as the superposition of the two frequencies $|\omega_{as1}\rangle + |\omega_{as2}\rangle$. What is more, adjusting one of the FWM signals will have an effect on the other. The group velocities of these two FWM fields could be adjusted by tuning the intensity or frequency detuning of the pump beam. Such a bichromatic field could also be useful in the cross-phase modulation of weak pulses at the low light level.

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References

[1] Fleischhauer M, Imamoglu A and Marangos J P 2005 Rev. Mod. Phys. 77 633
[2] Harris S E 1997 Phys. Today 50 36
[3] Boller K J, Imamoglu A and Harris S E 1991 Phys. Rev. Lett. 66 2593
[4] Li Y and Xiao M 1996 Opt. Lett. 21 1064
   Lu B, Burkett W H and Xiao M 1998 Opt. Lett. 23 804
[5] Zibrov A S, Matsko A B, Kocharovskaya O, Rostovtsev Y V, Welch G R and Scully M O 2002 Phys. Rev. Lett. 88 103601
[6] Rostovtsev Y V, Sariyanni Z E and Scully M O 2006 Phys. Rev. Lett. 97 113001
[7] Balic V, Braje D A, Kolchin P, Yin G Y and Harris S E 2005 Phys. Rev. Lett. 94 183601
[8] Phillips D F, Fleischhauer A, Mair A, Walsworth R L and Lukin M D 2001 Phys. Rev. Lett. 86 783–6

New Journal of Physics 14 (2012) 073047 (http://www.njp.org/)
[9] Phillips N B, Gorshkov A V and Novikova I 2011 Phys. Rev. A 83 063823
[10] Chen Y-F, Wang S-H, Wang C-Y and Yu I A 2005 Phys. Rev. A 72 053803
[11] Chen Y-F, Kuan P-C, Wang S-H, Wang C-Y and Yu I A 2006 Opt. Lett. 31 3511–3
[12] Du S, Wen J and Rubin Morton H 2008 J. Opt. Soc. Am. B 25 C98
[13] Du S, Kolchin P, Belthangady C, Yin G Y and Harris S E 2008 Phys. Rev. Lett. 100 183603
[14] Kolchin P, Du S, Belthangady C, Yin G Y and Harris S E 2006 Phys. Rev. Lett. 97 113602
[15] Balic’ V et al 2005 Phys. Rev. Lett. 94 183601
[16] Shiau B-W, Wu M-C, Lin C-C and Chen Y-C 2011 Phys. Rev. Lett. 106 193006
[17] Schmidt H and Imamog lu A 1996 Opt. Lett. 21 1936
[18] Hau L V et al 1999 Nature 397 594
[19] Kang H and Zhu Y 2003 Phys. Rev. Lett. 91 093601
[20] Ramelow S et al 2009 Phys. Rev. Lett. 103 253601
[21] Zhang Y P, Brown A W and Xiao M 2007 Phys. Rev. Lett. 99 123603
[22] Zhang Y P, Khadka U, Anderson B and Xiao M 2009 Phys. Rev. Lett. 102 013601
[23] Yang X H, Sheng J T, Khadka U and Xiao M 2011 Phys. Rev. A 83 063812
[24] Yang X H, Sheng J T, Khadka U and Xiao M 2012 Phys. Rev. A 85 013824
[25] Liu Y, Wu J H, Shi B S and Guo G C 2012 Chin. Phys. Lett. 29 024205
[26] Wen J-M and Rubin M H 2006 Phys. Rev. A 74 023808
[27] Wen J-M and Rubin M H 2006 Phys. Rev. A 74 023809
[28] Wang J, Zhu Y, Jiang K J and Zhan M S 2003 Phys. Rev. A 68 063810
[29] Yang G Q, Xu P, Wang J, Zhu Y and Zhan M S 2010 Phys. Rev. A 82 045804
[30] Wu Y 2005 Phys. Rev. A 71 053820
[31] Wu Y and Yang X 2004 Phys. Rev. A 70 053818