Electromagnetically induced transparency-assisted four-wave mixing process in the diamond-type four-level atomic system

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Abstract

With electromagnetically induced transparency (EIT)-assisted configuration, we study the third-order nonlinear four-wave mixing (FWM) process in a diamond-type four-level atomic system both theoretically and experimentally. Following the proposal by the recent study (Willis et al., 2009), we introduce EIT contribution to the theoretical model which will enhance the conversion efficiency of the nonlinear process and narrow the linewidth of the FWM signal. By means of the coherent EIT effect, we get higher conversion efficiency at lower power level of incident beam in such atomic system. Compare to our previous models, the conversion efficiency in such diamond-type atomic system is much smaller which needs higher threshold temperature. In addition, the frequency dependences on incident beams reveal that the dipole transition of one-photon and two-photon processes affect this nonlinear process. Motivated by the proposal referred in [6], we introduce the EIT configuration to assist this third-order nonlinear process.

1. Introduction

With [1–4] or without [5,6] electromagnetically induced transparency (EIT) [7] configuration, various four-wave mixing (FWM) processes are obtained in various multi-level atomic systems. Enhanced FWM processes due to atomic coherence have been experimentally demonstrated [8]. The keys in such enhanced nonlinear optical processes include enhanced nonlinear susceptibilities and slowed laser beam propagation in the atomic medium, as well as greatly reduced linear absorption of the generated optical fields due to EIT [9,10]. With large optical Kerr coefficients, highly efficient FWM in nitrobenzene liquids was also investigated [11]. Recently, a group in Maryland [5,6] develops a diamond-type four-level atomic system to study nondegenerate FWM process at wavelength for telecommunication without EIT configuration. In the process of the generation of FWM signal, the most important consideration is the conversion efficiency. The research work [12] showed that one can obtain resonantly enhanced third-order susceptibility while at the same time inducing transparency of the media by means of EIT configuration, and then the conversion efficiency can be substantially improved. Many groups use EIT configuration to enhance the FWM process or even six-wave mixing (SWM) process [8,13] in a multi-level atomic system and demonstrate that this is a benefit method to control the nonlinear process. Motivated by the proposal referred in [6], we introduce the EIT configuration to assist this third-order nonlinear process.

In this paper, with the EIT configuration we investigate the non-degenerate FWM process in a diamond-type four-level atomic system both theoretically and experimentally. We demonstrate that the conversion efficiency of the FWM process can be enhanced and the linewidth of the FWM signal can be narrowed owing to the contribution of EIT in the diamond-type four-level atomic system. Higher conversion efficiency with EIT-assisted configuration can be get at the same power level of the incident beam in such atomic system compared with the work in Ref. [6]. In addition, the frequency dependences on incident beams is studied, and the results reveal that the dipole transition of one-photon and two-photon processes will affect this nonlinear process. Compare to our previous works [4,8], the conversion efficiency of the diamond-type in the FWM process is much smaller, so the generation of the FWM signal in such atomic system needs higher threshold temperature in this paper.

2. Basic theory

Fig. 1 shows a diamond-type four-level atomic system in rubidium 85 together with the applied and generated light fields and the schematic experiment setup performed in this paper. The relevant energy levels formed by a ground state |1⟩ (5S 1/2, F = 3) and three excited states |2⟩ (5P 3/2), |3⟩ (5P 1/2) and |4⟩ (5D 3/2) are coupled by...
three incident continuous-wave (cw) laser beams as shown in Fig. 1(a). Laser beam $E_1(\omega_1)$ with detuning $\Delta_1(=\omega_1-\omega_{21})$, where $\omega_0$ is the frequency difference between energy levels $|0\rangle$ and $|1\rangle$, is emitted from an external-cavity diode laser (ECDL) as a scanning field connected to the transition between energy levels $|1\rangle$ and $|2\rangle$. The second laser beam $E_2(\omega_2)$ (with frequency detuning $\Delta_2$) is coupled to the transition between $|1\rangle$ and $|3\rangle$, which forms a V-type EIT configuration with the levels $|1\rangle$, $|2\rangle$, $|3\rangle$, and $|4\rangle$. For second laser beam $E_2$, the V-type EIT configuration is satisfied ($\Delta_1 = \Delta_2 = 0$), therefore, the V-type EIT window can be moved by changing the frequency detuning of $E_1$ and $E_2$. In addition, the transition between $|2\rangle$ and $|4\rangle$ is driven by the third laser $E_3(\omega_3)$ (with frequency detuning $\Delta_3$) counter-propagating with $E_1$, therefore, a cascade-type EIT configuration [15] with two-photon Doppler-free condition ($\Delta_1 + \Delta_3 = 0$) is established with the levels $|1\rangle$, $|2\rangle$, $|3\rangle$, and $|4\rangle$. The cascade-type EIT window can also be moved by the frequency detuning of $E_1$ and $E_2$. So in the V-type ($|1\rangle$, $|2\rangle$, $|3\rangle$, and $|4\rangle$) and cascade-type ($|1\rangle$, $|2\rangle$, $|3\rangle$, and $|4\rangle$) EIT subsystems in the diamond-type four-level atomic system form two EIT windows. These two EIT windows can either overlap or be separated by changing the frequency detuning of $E_1$, $E_2$, and $E_3$ laser beams. Each incident beam is focused on the middle of the rubidium vapor cell with the lens and the waist of each beam is approximately 1 mm. In the experiment, the polarizations of the incident beam are calibrated by half-wave plate and polarized-beam splitter (PBS) and then the polarization of the generated field is determined according to the susceptibility of isotropy medium. As shown in Fig. 1(b), the incident beams $E_1$, $E_3$ are horizontally polarized, and $E_2$ is vertically polarized. So the generated FWM signal should be vertically polarized. Via third-order nonlinear process $\chi^{(3)}$, the FWM signal $E_{\Delta}$ (from $\chi^{(3)}E_1E_2E_3$) is generated from the upper branch $|3\rangle$ and $|4\rangle$ with EIT-assisted. According to the momentum conservation and energy conservation, the phase-match condition and frequency relation are $k_3 = k_5 + k_2 - k_1$ and $\omega_3 = \omega_1 + \omega_2 - \omega_1$. The FWM signal $E_{\Delta}$ counter-propagates with $E_1$ and with a very small angle (see Fig. 1(b)) due to $|k_2| < |k_1| < |k_3| < |k_4|$ and can be separated from the laser beam $E_1$ through a PBS cube and detected by an avalanche photodiode detector (APD). In the experimental process we use saturated absorption technique (not shown in figure) and EIT peaks to calibrate the positions of the coupling and pump beams on the probe spectrum. To do these, we use a second auxiliary rubidium vapor cell with three beams separated from above mentioned three ECDLs. The three beams are arranged to satisfy the EIT configurations (lambda type $|1\rangle$, $|2\rangle$, $|3\rangle$, and $|4\rangle$) to monitor the transition positions of each beam.

The key point we are interested is the conversion efficiency of this nonlinear process. Following the proposal by Ref. [6], in this paper these four beams are arranged to fulfill the EIT configuration to increase the FWM efficiency in the diamond-type atomic system. In addition, the reasons for a narrow sub-Doppler spectrum feature of the generated FWM signal is not only the velocity selective [6], but also the coherent EIT effect [12]. To better understanding these characteristics, we give a brief theoretical model to treat the EIT-assisted third-order nonlinear process by the density-matrix formalism and the Maxwell–Bloch (MB) equations [16]. For simplicity, the velocity due to thermal atoms was not considered since there is a detail discussion in Ref. [6]. According to the density-matrix formalism, the relevant density elements corresponding to the linear susceptibility $\chi^{(1)}$ (relating to EIT effect of FWM beam) [17] and the third-order nonlinear susceptibility $\chi^{(3)}$ (relating to the FWM signal) are:

$$
\rho_{41}^{(1)} = \frac{iG_3}{\left(\Gamma_4 + \lambda d_4 \right) + \frac{G_1^2}{\lambda d_3} + \frac{G_2^2}{\lambda d_2} + \frac{G_3^2}{\lambda d_1}} + \frac{iG_0}{\left(\Gamma_4 + \lambda d_4 \right)} \left[\left(\Gamma_4 + \lambda d_4 \right) + \frac{G_1^2}{\lambda d_3} + \frac{G_2^2}{\lambda d_2} + \frac{G_3^2}{\lambda d_1}\right],$$

$$
\rho_{41}^{(3)} = -\frac{iG_0}{\lambda d_1} + \frac{iG_3}{\lambda d_4} \left[\frac{G_1^2}{\lambda d_3} + \frac{G_2^2}{\lambda d_2} + \frac{G_3^2}{\lambda d_1}\right],
$$

where $G_i(i = 1, 2, 3)$ is the Rabi frequency, and $\Gamma_i$ is the spontaneous emission rate from states $|1\rangle$ to $|i\rangle$. $G_0 = G_1G_2G_3$, $d_1 = \lambda - \Gamma_1$, $d_2 = \lambda - \Gamma_2$, $d_3 = \lambda - \Gamma_3$, $d_4 = \lambda - \Gamma_4$, $d_5 = \lambda - \Gamma_5$, and $d_6 = \lambda - \Gamma_6$. Then we use MB equation to seek how EIT effect can enhance the FWM efficiency. Assuming no depletion of the incident beams, the wave equation can be written as [12]:

$$
\frac{\partial E_4}{\partial z} = -i\kappa \chi^{(1)} |E_4| + i|\chi^{(1)}| |E_4| + A k |E_4| = -\frac{3}{2} k P_4,
$$

where $\kappa = \omega_0/2c$, $P_4$ is the polarization of beam $E_4$. The second term and third term of Eq. (2) are related to loss and dispersion, respectively. So, from Eqs. (1) and (2) [12,17], we can get the conversion efficiency of the FWM process is proportional to $R \times |\chi^{(3)}| |\chi^{(1)}|$. Apparently, EIT effect of the beam $E_4$ which can reduce even cancel the denominator, increases the FWM efficiency.

### 3. Experimental results and discussion

Now, let us concentrate on the experiment. We firstly get the FWM signal (lower curve) at 762 nm by scanning the beam $E_1$ around the D2 transition (upper curve of $^{85}\text{Rb}$ from $S_{1/2}$, $F = 3$) as shown in Fig. 2(a). In this process, the power of each incident beam is $P_{780} = 5$ mW, $P_{795} = 10$ mW, and $P_{776} = 15$ mW, respectively. As usual, the zero point of the horizontal axis is calibrated by choosing the lowest point of the Doppler absorption profile, approximately corresponding to the highest $hf$ transition probability, i.e. $S_{1/2}$, $F = 3$ to $P_{776}$. The detuning of each incident beam is carefully controlled to fulfill the two-photon resonance condition, and then the EIT windows are overlapped ($\Delta_1 = \Delta_2 = -\Delta_3 \approx 300$ MHz). The FWM signal is restrained in these

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**Fig. 1.** The diamond-type four-level atomic system in rubidium 85 (a) and the schematic experiment setup (b). Double-headed arrows and filled dots denote horizontal polarization and vertical polarization of incident beams (black lines with arrow), respectively.

**Fig. 2.** (a) Observation of the spectrum profiles of the scanning field $E_1$ around D2 transition of $^{85}\text{Rb}$ (from $S_{1/2}$, $F = 3$) (upper curve) and the FWM signal $E_4$ (lower curve). (b) The conversion efficiency versus the temperature of the atomic vapor. $\Delta_1 = \Delta_2 = -\Delta_3 \approx 300$ MHz.
windows which will enhance and narrow the signal. Then, we focus on the conversion efficiency by varying the temperature of the cell as shown in Fig. 2(b). The curve reflects that there exists a threshold temperature which is approximately 85 °C. Compare to our previous experimental system for the FWM process such as cascade-type [8] for lambda-type [4], the conversion efficiency of this diamond-type is much smaller. So the generation of FWM is too small and needs higher threshold temperature. In addition, this nonlinear process.

Next, we investigate the frequency dependence on the coupling beams $E_2$ and $E_3$, respectively. The experimental condition is the same as the mentioned above except the temperature is fixed at 103 °C. Fig. 3 shows the evolution curve of the frequency dependence by carefully varying the frequency of beam (a) $E_2$ or (b) $E_3$. Every time we make one EIT position fix at $\Delta_1 = 230$ MHz. Both evolution curves in Fig. 3 shows that the maximum efficiency point corresponds to the resonant point of three incident beams, i.e. $\Delta_1 = \Delta_2 \approx 230$ MHz. Furthermore, we can conclude that the frequency selection of the dipole transition around D1 and D2 lines determines the efficiency distribution, where the transition between $5S_{1/2}, F = 3$ and $5P_{3/2}, F = 2$ is higher than $5S_{1/2}, F = 3$ to $5P_{3/2}, F = 2$, and also the transition between $5S_{1/2}, F = 3$ and $5P_{3/2}, F' = 2.3$ have more contribution to the two-photon process between energy levels [1] → [4].

Finally, the power dependences of the conversion efficiency on the beams $E_2$ and $E_3$ are respectively studied. We use the same experimental condition as before and make the powers of beams $E_2$ and $E_3$, respectively, as varying parameters. When the beam $E_3$ is fixed at $P_{776} = 10$ mW, Fig. 4(a) shows the intensity of the obtained FWM signal as the varied power of beam $E_2$. At the same time, the power dependence on the beam $E_2$ at fixed power of beam $E_2$ ($P_{776} = 10$ mW) is shown in Fig. 4(b). From the two measured curves, we can find the tendencies of the curves are the same, and the signal intensities both increase as the power increase. The maximum conversion efficiency is approximately $3 \times 10^{-4}$ responding to the field $E_2$. We believe that it will be up to higher intensity of FWM by enhancing the power of incident beams. Compare to Ref. [6], in our experiment, we got higher efficiency with lower powers, which can be attributed to the EIT-assisted configuration and lower transition levels ($|4\rangle \rightarrow |5D_{3/2}\rangle$).

4. Conclusion

In summary, we study the FWM process in a diamond-type four-level atomic system with EIT-assisted configuration both theoretically and experimentally. Compare to Ref. [6], besides velocity selection, we introduce EIT contribution to the theoretical model which will enhance the conversion efficiency of the nonlinear process and narrow the linewidth of the FWM signal. With EIT-assisted configuration, we get higher conversion efficiency at lower power level of incident beam in such atomic system. Compare to our previous model, the conversion efficiency is much smaller which needs higher threshold temperature. In addition, the frequency dependences on incident beams reveal that the dipole transition of one-photon and two-photon processes affect this nonlinear process.

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References