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Co-existing of dressed non-linear gain and electromagnetically induced absorption

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ABSTRACT

The dressed parametric four-wave mixing (FWM) process has been investigated in hot atomic rubidium vapor. We use a strong pumping field to generate entangled photon pairs of spontaneous parametric FWM (SP-FWM) which can be enhanced by an external dressing effect. Seeding probe beam into the Stokes or anti-Stokes (SP-FWM) channel will form the parametric amplified FWM (PA-FWM) process, then the non-linear gain and electromagnetically induced absorption (EIA) are observed, caused by the internal dressing effect. However, with scanning of pumping field the absorbing background will vanish, which will result in drastic increase in PA-FWM signal gain.

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1. Introduction

Atomic coherence in spontaneous parametric four-wave mixing (SP-FWM) [1,2] has been widely studied, due to the potential application in entangled and squeezed states [3] of quantum optics and cascaded nonlinear optics [4,5]. Applying a high power pumping beam into a thermal rubidium atomic vapor would induce a cycle of four transitions, which would stimulate the emission of entangled Stokes and anti-Stokes photons [3], thus the "double-Λ" FWM processes were introduced. For the process without seeding, the output is the two-mode squeezed state of FWM [6,7]. The instantaneous electric fields of the Stokes and anti-Stokes channels are averagely zero, while their fluctuations are quantum-correlated [4]. The mentioned process can serve as a linear phase-insensitive or phase-sensitive [8,9] amplifier by fitting experimental parameters, for the large scale of third-order nonlinear susceptibility will lead to an obvious quantum gain.

Recently, the results of seeding a weak probe beam into Stokes or Anti-Stokes channel have also attracted a lot of attention, where the non-input channel is called conjugate [10,11], and the twin beams are strongly correlated [12]. The process could be defined as Parametric Amplified Four-Wave Mixing (PA-FWM), then probe and conjugate beams can be both amplified [8] but with different multiples of Ω and $\Omega - 1$ [4], where the correlated pairs are with high generation rates and produce squeezed states with narrow bandwidths [13].

In this paper, we demonstrate an external dressing beam from the opposite direction of pumping field in the non-seeded system would produce strong dressing effect, which can modify the SP-FWM cone of pumping field. Moreover, instead of probe field, the pumping field is scanned for the first time in the PA-FWM process, which is advantageous over former experiments [9–11]. For one thing, the strong background will diminish by scanning dressing field, which allows the appearance of electromagnetically induced absorption (EIA) [14] in the resonant regions; for another, the values of observed gains would be greater, and there exist competition and transformation between EIA and gain process.

2. Experimental setup

A strong pumping beam ($\boldsymbol{E}_1$) from a Ti: sapphire laser is injected into the rubidium cell through polarization beam splitter (PBS) where ω_1, $\boldsymbol{k}_1$ and $\boldsymbol{G}_1$, are frequency, wave vector and Rabi

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frequency of $\boldsymbol{E}_1$, respectively. We use 780.2 nm wavelength and power up to 500 mw. The pumping field $\boldsymbol{E}_1$ will generate two weak fields $\boldsymbol{E}_s$ and $\boldsymbol{E}_{as}$, satisfying the phase matching conditions $\boldsymbol{k}_s = 2\boldsymbol{k}_1 - \boldsymbol{k}_{as}$ and $\boldsymbol{k}_{as} = 2\boldsymbol{k}_1 - \boldsymbol{k}_s$, respectively. The Stokes and anti-Stokes signals are detected by two balanced homodyne detectors, which are set at the same angle on both sides to the axis of pumping beam $\boldsymbol{E}_1$. Moreover, an avalanche photodiode detector (APD) is placed near the cell for detecting fluorescence signal, and another detector is placed on the axis of pumping beam for detecting transmission signal. The resonant transition frequency between the ground state $5S_{1/2}$ ($|0\rangle$) and an excited state $5P_{3/2}$ ($|2\rangle$) is Ω_1. When a weak dressing field $\boldsymbol{E}_2$ (ω_2, $\boldsymbol{k}_2$, $\boldsymbol{G}_2$ and 776.16 nm) is involved, the frequency between $5P_{3/2}$ ($|2\rangle$) and $5D_{5/2}$ ($|2\rangle$) is Ω_2. The dressing field will cause electromagnetically induced Transparency (EIT) and EIA on the basic resonant signal. The energy-level diagrams of the two experimental conditions are shown in Fig. 1 (b) and (c), which represent the resonant state.

Providing the weak horizontal polarization probe beam $\boldsymbol{E}_\text{p}$ (ω_p, $\boldsymbol{k}_\text{p}$, $\boldsymbol{G}_\text{p}$) of approximate 100 μw into the atomic vapor, which is excited by an external cavity diode laser(ECDL), a PA-FWM process will occur in the three level atomic configuration (Fig. 1(d) and (e)). The two ground fine states ($F = 2$, $|0\rangle$ and $F = 3$, $|1\rangle$) have a difference of 3 GHz in frequency. The probe ($\boldsymbol{E}_\text{p}$) and the conjugate ($\boldsymbol{E}_\text{c}$ (ω_c, $\boldsymbol{k}_\text{c}$, $\boldsymbol{G}_\text{c}$)) satisfy the phase matching conditions $\boldsymbol{k}_\text{p} = 2\boldsymbol{k}_1 - \boldsymbol{k}_\text{c}$ and $\boldsymbol{k}_\text{c} = 2\boldsymbol{k}_1 - \boldsymbol{k}_\text{p}$, respectively. The intensity of probe signal is detected by the detector in Stokes or anti-Stokes channel. All beams are focused by lenses with focal length of 500 mm in front of the cell and the beams are intersected at the same central point inside the cell. The diameters of $\boldsymbol{E}_1$ and $\boldsymbol{E}_\text{p}$ are 0.8 mm and 0.5 mm, respectively. The scale of 10 mm rubidium cell with Brewster's angle is wrapped by μ-metal and heated to 70–150 °C. By seeding $\boldsymbol{E}_\text{p}$ into the Stokes or anti-Stokes channel of the SP-FWM, the transmission signal in pumping field will be amplified due to the PA-FWM process. The observed output in probe field will result from the Raman absorption, EIA effect, parametrical amplification process and dressing effect by scanning $\boldsymbol{E}_\text{p}$. Nonetheless, when scanning $\boldsymbol{E}_1$ the absorbing background will vanish, which results in drastic increase in gain of signal.

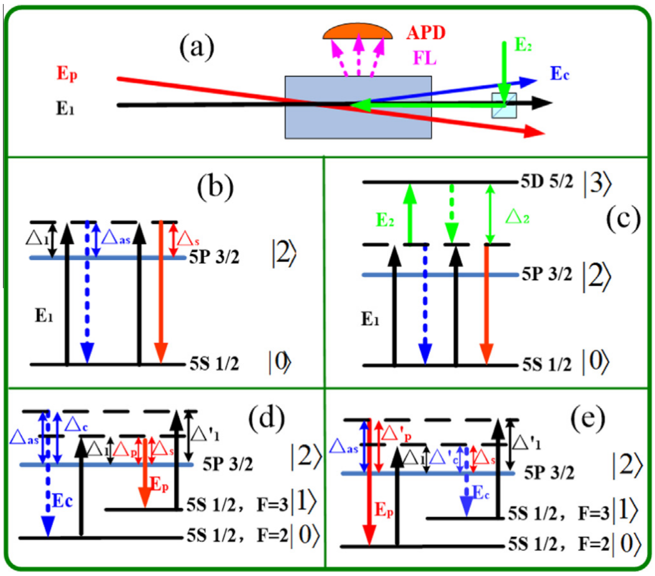

Fig. 1. (a) Experimental setup. $\boldsymbol{E}_1$: pumping field; $\boldsymbol{E}_2$: dressing field; $\boldsymbol{E}_\text{p}$: probe field; $\boldsymbol{E}_\text{c}$: conjugate field; FL: fluorescence signal; APD: avalanche photodiode detector. (b) Energy-level diagram with seeding $\boldsymbol{E}_1$ only. (c) Energy-level diagram with seeding $\boldsymbol{E}_1$ and $\boldsymbol{E}_2$. (d) Energy-level diagram with $\boldsymbol{E}_1$ and seeding $\boldsymbol{E}_\text{p}$ into Stokes channel. (e) Energy-level diagram with $\boldsymbol{E}_1$ and seeding $\boldsymbol{E}_\text{p}$ into anti-Stokes channel.

3. Basic theory

3.1. SP-FWM without injection

When a pumping beam $\boldsymbol{E}_1$ is detuned from $5S_{1/2}$ to $5P_{3/2}$ in the rubidium vapor, a conical emission is observed and twin photons are produced in output Stokes and anti-Stokes channels (denoted as a and b, respectively). The energy-level diagram is shown in Fig. 1(b). The Hamiltonian of such a phenomenon can be expressed as

$$\hat{H} = \frac{g}{v}\left(\hat{a}^{+}\hat{b}^{+} + \hat{a}\hat{b}\right) \tag{1}$$

where $\hat{a}^{+}\hat{b}^{+}$ is the creation (annihilation) operator that acts on the electromagnetic excitation of the Stokes channel, whereas $\hat{a}\hat{b}$ acts on the anti-Stokes channel, v is the group velocity of the light in the nonlinear medium. $g = |\chi^{(3)}\boldsymbol{E}_1\boldsymbol{E}_1| = |N\mu_{10}^2\rho_{s/as}^{(3)}/\hbar\varepsilon_0 G_{s/as}|$ is the pumping parameter of the amplifier, which depends on the nonlinearity $\chi^{(3)}$ and the amplitude of pumping field $\boldsymbol{E}_1$. Unlike nonlinear crystal, the nonlinearity $\chi^{(3)}$ of such medium is a function of the density matrix elements described by their perturbation chains $\rho_{00}^{(0)} \xrightarrow{\omega_1} \rho_{20}^{(1)} \xrightarrow{\omega_{as}} \rho_{00}^{(2)} \xrightarrow{\omega_1} \rho_{20(s)}^{(3)}$ (Stokes signal) and $\rho_{00}^{(0)} \xrightarrow{\omega_1} \rho_{20}^{(1)} \xrightarrow{\omega_s} \rho_{00}^{(2)} \xrightarrow{\omega_1} \rho_{20(as)}^{(3)}$ (anti-Stokes signal) via the Liouville pathway [10] and can be written as

$$\rho_{20(as)}^{(3)} = -iG_sG_1^2\Big/\left(d_{20}d_{00(s)}d'_{20(s)}\right), \tag{2a}$$

$$\rho_{20(s)}^{(3)} = -iG_{as}G_1^2\Big/\left(d_{20}d_{00(as)}d'_{20(as)}\right), \tag{2b}$$

where $d_{20} = \Gamma_{20} - i\Delta_1$, $d_{00(s)} = \Gamma_{00} - i(\Delta_1 - \Delta_s)$, $d_{00(as)} = \Gamma_{00} - i(\Delta_1 - \Delta_{as})$, $d'_{20(s)} = \Gamma_{20} - i(2\Delta_1 - \Delta_s)$, $d'_{20(as)} = \Gamma_{20} - i(2\Delta_1 - \Delta_{as})$, $\boldsymbol{G}_i = \mu_{ij}\boldsymbol{E}_{ij}/\hbar$ $(i, j = s, as, c, p)$ is the Rabi frequency, $\Gamma_{ij} = (\Gamma_i + \Gamma_j)/2$ is the decoherence rate between $|i\rangle$ and $|j\rangle$; Δ_i is the detuning between the resonant transition frequency Ω_i and the laser frequency ω_i of $\boldsymbol{E}_i$, denoted as $\Delta_i = \omega_i - \Omega_i$. In this experiment, the SP-FWM process occurs at the resonant detuning $\Delta_1 = \Delta_s = \Delta_{as}$, shown in Fig. 1(b). When Stokes and anti-Stokes fields propagate in the nonlinear medium, the numbers of photons measured at the two channels are

$$\begin{aligned}\langle\hat{a}_{out}^{+}\hat{a}_{out}\rangle = {} & \frac{1}{2}\left[\cos\left(2t\sqrt{AB}\sin\frac{\varphi_1+\varphi_2}{2}\right)\right.\\ & \left.+\cosh\left(2t\sqrt{AB}\cos\frac{\varphi_1+\varphi_2}{2}\right)\right]\times\frac{A}{B},\end{aligned} \tag{3a}$$

$$\begin{aligned}\langle\hat{b}_{out}^{+}\hat{b}_{out}\rangle = {} & \frac{1}{2}\left[\cos\left(2t\sqrt{AB}\sin\frac{\varphi_1+\varphi_2}{2}\right)\right.\\ & \left.+\cosh\left(2t\sqrt{AB}\cos\frac{\varphi_1+\varphi_2}{2}\right)\right]\times\frac{B}{A},\end{aligned} \tag{3b}$$

where A and B are the moduli [4], φ_1 and φ_2 are the phase angles of $\rho_{21(s)}^{(3)} = Ae^{i\varphi_1}$ and $\rho_{20(as)}^{(3)} = Be^{i\varphi_2}$, respectively. Therefore, the outputs of Stokes and anti-Stokes channels of SP-FWM are at the same value as

$$\Omega = \frac{1}{2}\left[\cos\left(2t\sqrt{AB}\sin\frac{\varphi_1+\varphi_2}{2}\right) + \cosh\left(2t\sqrt{AB}\cos\frac{\varphi_1+\varphi_2}{2}\right)\right]. \tag{4}$$

If we inject $\boldsymbol{E}_2$ into the SP-FWM as a dressing field, the ladder-type three-level atomic configuration is formed, as shown in Fig. 1 (c). Thus, Eq. (2) will be rewritten as

$$\rho_{20(as)}^{(3)} = -iG_sG_1^2\Big/\left[d_{00(s)}d'_{20(s)}(G_2^2/d_{30} + d_{20})\right], \tag{5a}$$

$$\rho_{20(s)}^{(3)} = -iG_{as}G_1^2\Big/\left[d_{00(as)}d'_{20(as)}(G_2^2/d_{30} + d_{20})\right], \tag{5b}$$

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