Article ID: 1004-4213(2011)08-1161-5

Frequency Up- and Down-conversions in Two-mode Cavity

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Abstract: A scheme was proposed to construct bilinear and quadratic Hamiltonians for frequency up- and down-conversions in cavity quantum electrodynamics (QED). Generally, in nonlinear optics, the interaction that the energe swaps between different optic modes without atomic transition is named frequency conversion. The proposed scheme was based on the interactions of a single four-level atom simultaneously with two classical driving fields and a two-mode cavity field, which is in the domain of four-wave mixing . By initially preparing the atom in a suitable state, each pump light was resonant with its transition, and two quantum modes were large tune to the other two transition, respectively, In the strong laser regime, the atomic degrees of freedom could be decoupled from the cavity degrees of freedom and the frequency conversion could be realized for the cavity modes. Due to the different initial states and interactions between optic fields and atom, frequency up- and down-conversions arose, respectively. After the preparation of squeezed operation respect to Frequency down-conversion, a discussion on the feasibility of experiment was given and the theoretical value was obtained. The advantage of this proposal is to realize the transition using two cascade photons, which is dipole-forbidden in a cascade structure atom, with high efficiency. The proposal will be useful for optical quantum control and fundamental tests of quantum theory.

Key words: Frequency conversions; Cavity quantum electrodynamics

CLCN: N91 **Document Code**: A **doi**: 10.3788/gzxb20114008.1161

0 Introduction

Parametric frequency conversion is traditionally for traveling fields in nonlinear optics and recently has been extended to cavity fields in quantum optics. It has many important applications in investigating fundamental quantum phenomena. Many efforts have been devoted to generate the squeezed states[1-11] and two-photon states[4-11], to test sub-Poissonian statistics[12] and Bell's inequalities[13], to improve the signal-to-noise ratio in optical communication[14-15] and to measure the gravitational waves[16-17]. Apart from these applications, the frequency conversion mechanism has also been used for single-photon interference to demonstrate Boson commutation[18]. The frequency up-conversion has connection to a beam splitter in quantum optics, which generates an active rotation of two cavity modes, while a parametric down-conversion can be directly used to generate a two-mode squeezed state[5] which is a very important quantum entangled state. The two-mode squeezed state can be generated from a laser-driven V-type three-level atom inside a cavity[6] and from a single atom with respect to a low-Q cavity[7]. Meanwhile, it is widely used in quantum cryptography[19-20], quantum dense coding[21], quantum teleportation[22-23], and large-scale quantum computing[24-25].

Several recent studies have been devoted to mapping the frequency conversion mechanism into a two-mode cavity[5, 8-11]. All these protocols need to drive a dipole-forbidden transition with a classical field via two-photon processes or other mechanisms, however, the couplings in these mechanisms are usually very weak. Here in this paper, we present a scheme to realize the frequency conversion mechanism with a diamond atomic configuration in cavity QED without the

Foundation item: The National Natural Science Foundation of China (No. 60978009) and the National Basic Research Program of China (No. 2009CB929604, No. 2007CB925204)

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Received date: 2011-03-07 **Revised date**: 2011-04-22

requirement of driving the dipole-forbidden transition and the efficiency is comparable with that of Ref. [5]. In our scheme, based on the interactions of a single four-level atom simultaneously with two classical driving fields and a two-mode cavity, the bilinear and quadratic Hamiltonians for frequency up-and down-conversions could be realized.

1 Generation of frequency up-conversion

Now we introduce the model. We deposit a four-level atom driven by two classical fields in a two-mode cavity. As shown in Fig. 1, the atomic states are labeled by $|e\rangle$, $|r\rangle$, $|g\rangle$ and $|s\rangle$, respectively. The classical field drives the transition $|e\rangle\rightarrow|r\rangle$ ($|s\rangle\rightarrow|r\rangle$) with the Rabi frequency Ω_1 (Ω_2) resonantly. The transition $|g\rangle\rightarrow|e\rangle$ ($|g\rangle\rightarrow|s\rangle$) is driven by the cavity mode with the coupling constant g_1 (g_2) and detuning Δ_1 (Δ_2), respectively. Thus, in the interaction picture, the Hamiltonian is $H_I=H_0+H_1$, where

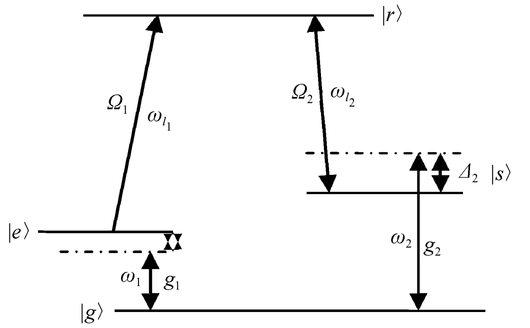

Fig. 1 The interaction model for the frequency up-conversion: a four-level atom interacts with two cavity-modes (coupling constants g_1 and g_2, detunings Δ_1 and Δ_2) and two classical fields (Rabi frequencies Ω_1 and Ω_2)

$$H_0=\Omega_1|e\rangle\langle r|+\Omega_2|r\rangle\langle s|+H.c. \tag{1}$$

$$H_1=g_1a|e\rangle\langle g|e^{i\Delta_1 t}+g_2b|s\rangle\langle g|e^{-i\Delta_2 t}+H.c. \tag{2}$$

where a^+ (a) and b^+ (b) are creation (annihilation) operators of cavity modes a and b, respectively.

We express the H_0's dressed states as $|A_0\rangle$, $|A_1\rangle$ and $|A_2\rangle$ with the corresponding eignvalues 0, Ω, $-\Omega$, respectively

$$\begin{aligned}|A_0\rangle&=\frac{1}{\Omega}(\Omega_1|s\rangle-\Omega_2|e\rangle)\\|A_1\rangle&=\frac{1}{\sqrt{2}}[\frac{1}{\Omega}(\Omega_1|e\rangle+\Omega_2|s\rangle)+|r\rangle]\\|A_2\rangle&=\frac{1}{\sqrt{2}}[\frac{1}{\Omega}(\Omega_1|e\rangle+\Omega_2|s\rangle)-|r\rangle]\end{aligned} \tag{3}$$

with $|A_0\rangle$, $|A_1\rangle$ and $|A_2\rangle$, the Hamiltonians H_0 and H_1 can be expressed as

$$H_0=\Omega(|A_1\rangle\langle A_1|-|A_2\rangle\langle A_2|) \tag{4}$$

$$\begin{aligned}H_1=&g_1a\frac{1}{\Omega}\left[\frac{\Omega_1}{\sqrt{2}}(|A_1\rangle+|A_2\rangle)+\Omega_2|A_0\rangle\right]\cdot\\&\langle g|e^{i\Delta_1 t}+g_2b\frac{1}{\Omega}\left[\frac{\Omega_2}{\sqrt{2}}(|A_1\rangle+|A_2\rangle)-\Omega_1|A_0\rangle\right]\cdot\\&\langle g|e^{-i\Delta_2 t}+H.c.\end{aligned} \tag{5}$$

where $\Omega^2=\Omega_1^2+\Omega_2^2$. We can rewrite the Hamiltonian H_1 in the interaction pictures with respect to H_0, then we have

$$\begin{aligned}H_1'=&g_1a\frac{1}{\Omega}\left[\frac{\Omega_1}{\sqrt{2}}(e^{i\Omega}|A_1\rangle+e^{-i\Omega}|A_2\rangle)+\Omega_2|A_0\rangle\right]\cdot\\&\langle g|e^{i\Delta_1 t}+g_2b\frac{1}{\Omega}\left[\frac{\Omega_2}{\sqrt{2}}(e^{i\Omega}|A_1\rangle+e^{-i\Omega}|A_2\rangle)-\Omega_1|A_0\rangle\right]\cdot\\&\langle g|e^{-i\Delta_2 t}+H.c.\end{aligned} \tag{6}$$

In the strong laser regime, $\Omega+\Delta_1\gg\frac{g_1\Omega_1}{\Omega}$, $\Omega+\Delta_2\gg\frac{g_2\Omega_2}{\Omega}$, $\Delta_1\gg\frac{g_1\Omega_2}{\Omega}$, $\Delta_2\gg\frac{g_2\Omega_1}{\Omega}$. Using the time-averaging method mentioned in Ref. [26] and neglecting the effect of rapidly oscillating, we transform the Hamiltonian (6) to the effective Hamiltonian

$$\begin{aligned}H_{\mathrm{eff}}=&C_1(aa^+|A_1\rangle\langle A_1|-a^+a|g\rangle\langle g|)+\\&C_2(bb^+|A_1\rangle\langle A_1|-b^+b|g\rangle\langle g|)+\\&C_3(a^+a|g\rangle\langle g|-aa^+|A_2\rangle\langle A_2|)+\\&C_4(b^+b|g\rangle\langle g|-bb^+|A_2\rangle\langle A_2|)+\\&C_5(aa^+|A_0\rangle\langle A_0|-a^+a|g\rangle\langle g|)+\\&C_6(b^+b|g\rangle\langle g|-bb^+|A_0\rangle\langle A_0|)+\\&C_7ab^+(|A_1\rangle\langle A_1|-|g\rangle\langle g|)e^{i\Gamma}+\\&C_8a^+b(|A_2\rangle\langle A_2|-|g\rangle\langle g|)e^{-i\Gamma}+H.c.\end{aligned} \tag{7}$$

where

$$C_1=(\frac{g_1\Omega_1}{\sqrt{2}\Omega})^2\frac{1}{\Omega+\Delta_1};\ C_2=(\frac{g_2\Omega_2}{\sqrt{2}\Omega})^2\frac{1}{\Omega+\Delta_2};$$

$$C_3=(\frac{g_1\Omega_1}{\sqrt{2}\Omega})^2\frac{1}{\Omega-\Delta_1};\ C_4=(\frac{g_2\Omega_2}{\sqrt{2}\Omega})^2\frac{1}{\Omega+\Delta_2};$$

$$C_5=\frac{g_1}{\Delta_1}(\frac{\Omega_2}{\Omega})^2;\ C_6=(\frac{\Omega_1}{\Omega})^2\frac{g_2^2}{\Delta_2};$$

$$C_7=\frac{g_1\Omega_1}{\sqrt{2}\Omega}\frac{g_2\Omega_2}{\sqrt{2}\Omega}\frac{(2\Omega+\Delta_1-\Delta_2)}{2(\Omega+\Delta_1)(\Omega-\Delta_2)};$$

$$C_8=\frac{g_1\Omega_1}{\sqrt{2}\Omega}\frac{g_2\Omega_2}{\sqrt{2}\Omega}\frac{(2\Omega-\Delta_1+\Delta_2)}{2(\Omega-\Delta_1)(\Omega+\Delta_2)}$$

$$\Gamma_1=\Delta_1+\Delta_2.$$

We set the atom in the ground state, and then we can neglect the dynamic evolution of the atom, thus only the Hamiltonian of the cavity remains

$$H_{\mathrm{eff}}=\gamma_a a^+a+\gamma_b b^+b-(\gamma ab^+e^{i\Gamma t}+H.c.) \tag{8}$$

where $\gamma_a=C_3-C_1-C_5$, $\gamma_b=C_2+C_6-C_4$, $\gamma=C_7+C_8$. With the rotation of the free terms, we obtain

$$H_{\mathrm{eff}}=\xi_1(t)ab^++\xi_1(t)^*a^+b \tag{9}$$

where $\xi_1(t)=-\gamma e^{i(\Gamma-\gamma_a+\gamma_b)t}$. From equation (9) the frequency up-conversion process can be expected, which generates an active rotation of the two cavity modes.

2 Generation of frequency down-conversion

Now we give a similar method to implement the parametric down-conversion (PDC) process. The appropriate Hamiltonian is

$$H_{\text{eff}}=\xi(t)ab+\xi(t)^{*}a^{+}b^{+} \tag{10}$$

The interaction model is shown in Fig. 2. Comparing with Fig. 1, now the classical field 2 (the cavity mode 1) couples the atomic transition $|e\rangle\leftrightarrow|g\rangle$ ($|s\rangle\leftrightarrow|r\rangle$), while the other two transitions are the same with that in Fig. 1. Thus the Hamiltonian reads

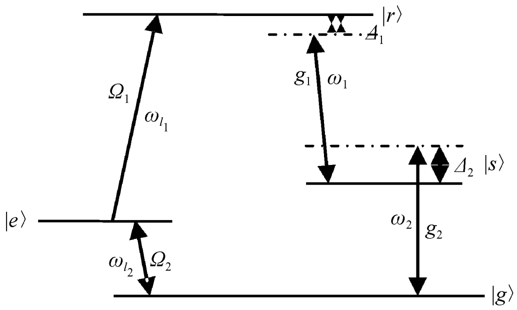

Fig. 2　The interaction model for the frequency down-conversion

$$H_0=\Omega_1|e\rangle\langle r|+\Omega_2|e\rangle\langle g|+H.c. \tag{11}$$

$$H_1=g_1a\sigma|r\rangle\langle s|\mathrm{e}^{\mathrm{i}\Delta_1 t}+g_2b|s\rangle\langle g|\mathrm{e}^{-\mathrm{i}\Delta_2 t}+H.c. \tag{12}$$

We express H_0's dressed states as $|B_0\rangle$, $|B_1\rangle$, $|B_2\rangle$ and the corresponding eignvalues are 0, Ω, $-\Omega$, respectively

$$\begin{aligned}|B_0\rangle&=\frac{1}{\Omega}(\Omega_1|g\rangle-\Omega_2|r\rangle)\\ |B_1\rangle&=\frac{1}{\sqrt{2}}\left[\frac{1}{\Omega}(\Omega_1|r\rangle+\Omega_2|g\rangle)+|e\rangle\right]\\ |B_2\rangle&=\frac{1}{\sqrt{2}}\left[\frac{1}{\Omega}(\Omega_1|r\rangle+\Omega_2|g\rangle)-|e\rangle\right]\end{aligned} \tag{13}$$

then the Hamiltonians H_0 and H_1 can be expressed as

$$H_0=\Omega(|B_1\rangle\langle B_1|-|B_2\rangle\langle B_2|) \tag{14}$$

$$\begin{aligned}H_1=&g_1a\frac{1}{\Omega}\left[\frac{\Omega_1}{\sqrt{2}}(\mathrm{e}^{\mathrm{i}\Omega}|B_1\rangle+\mathrm{e}^{-\mathrm{i}\Omega}|B_2\rangle)+\Omega_2|B_0\rangle\right]\cdot\\ &\langle s|\mathrm{e}^{\mathrm{i}\Delta_1 t}+g_1a^{+}\frac{1}{\Omega}|s\rangle\left[\frac{\Omega_1}{\sqrt{2}}(\mathrm{e}^{-\mathrm{i}\Omega}\langle B_1|+\mathrm{e}^{\mathrm{i}\Omega}\langle B_2|)+\right.\\ &\left.\Omega_2\langle B_0|\right]\mathrm{e}^{-\mathrm{i}\Delta_1 t}+g_2b^{+}\frac{1}{\Omega}\left[\frac{\Omega_2}{\sqrt{2}}(\mathrm{e}^{\mathrm{i}\Omega}|B_1\rangle+\mathrm{e}^{-\mathrm{i}\Omega}|B_2\rangle)-\right.\\ &\left.\Omega_1|B_0\rangle\right]\langle s|\mathrm{e}^{\mathrm{i}\Delta_2 t}+g_2b\frac{1}{\Omega}|s\rangle\left[\frac{\Omega_2}{\sqrt{2}}(\mathrm{e}^{-\mathrm{i}\Omega}\langle B_1|+\right.\\ &\left.\mathrm{e}^{\mathrm{i}\Omega}\langle B_2|)-\Omega_2\langle B_0|\right]\mathrm{e}^{-\mathrm{i}\Delta_2 t}\end{aligned} \tag{15}$$

where $\Omega^2=\Omega_1^2+\Omega_2^2$. In the interaction picture respect to the H_0, and in the strong laser regime $\Omega-\Delta_1\gg\frac{g_1\Omega_1}{\Omega}$, $\Omega-\Delta_2\gg\frac{g_2\Omega_2}{\Omega}$, $\Delta_1\gg\frac{g_1\Omega_2}{\Omega}$ and $\Delta_2\gg\frac{g_2\Omega_1}{\Omega}$, the effective Hamiltonian[26] without the high frequency terms is

$$\begin{aligned}H_{\text{eff}}=&C_1(aa^{+}|B_1\rangle\langle B_1|-a^{+}a|s\rangle\langle s|)+\\ &C_2(b^{+}b|B_1\rangle\langle B_1|-bb^{+}|s\rangle\langle s|)+\\ &C_3(a^{+}a|s\rangle\langle s|-aa^{+}|B_2\rangle\langle B_2|)+\\ &C_4(bb^{+}|s\rangle\langle s|-b^{+}b|B_2\rangle\langle B_2|)+\\ &C_9(aa^{+}|B_0\rangle\langle B_0|-a^{+}a|s\rangle\langle s|)+\\ &C_{10}(b^{+}b|B_0\rangle\langle B_0|-bb^{+}|s\rangle\langle s|)+\\ &C_{11}ab(|B_1\rangle\langle B_1|-|s\rangle\langle s|)e^{i\Gamma_2 t}+\\ &C_{12}ab(|s\rangle\langle s|-|B_2\rangle\langle B_2|)\mathrm{e}^{\mathrm{i}\Gamma_2 t}-\\ &C_{13}ab(|B_0\rangle\langle B_0|-|s\rangle\langle s|)\mathrm{e}^{\mathrm{i}\Gamma_2 t}+H.c.\end{aligned} \tag{16}$$

Where

$$C_9=\left(\frac{\Omega_2}{\Omega}\right)^2\frac{g_1^2}{(\Delta_1)};\ C_{10}=\left(\frac{\Omega_1}{\Omega}\right)^2\frac{g_2^2}{(\Delta_2)};$$

$$C_{11}=\frac{g_1\Omega_1}{4\Omega^2}\frac{g_2\Omega_2(2\Omega+\Delta_1+\Delta_2)}{(\Omega+\Delta_1)(\Omega+\Delta_2)};$$

$$C_{12}=\frac{g_1\Omega_1}{4\Omega^2}\frac{g_2\Omega_2(2\Omega-\Delta_1-\Delta_2)}{(\Omega-\Delta_1)(\Omega-\Delta_2)};$$

$$C_{13}=\frac{g_1\Omega_1}{2\Omega^2}\frac{g_2\Omega_2(\Delta_1+\Delta_2)}{\Delta_1\Delta_2};$$

$$\Gamma_2=\Delta_1-\Delta_2.$$

We prepare the initial state of the system in level $|s\rangle$, then only the dynamics of the cavity fields remains

$$H_{\text{eff}}=\lambda_a a^{+}a+\lambda_b bb^{+}+\lambda(ab\mathrm{e}^{\mathrm{i}\Gamma_2 t}+H.c.) \tag{17}$$

where $\lambda=-C_{11}+C_{12}+C_{13}$, $\lambda_a=-C_1+C_3-C_9$, $\lambda_b=-C_2+C_4-C_{10}$.

Furthermore, via a picture transformation we obtain the final Hamiltonian

$$H_{\text{eff}}=\xi_2(t)ab+\xi_2(t)^{*}a^{+}b^{+} \tag{18}$$

where $\xi_2(t)=\lambda\mathrm{e}^{\mathrm{i}(\Gamma_2+\lambda_a+\lambda_b)t}$ is the effective coupling constant. The result is what we expect. When we make $a=b$, the one-mode squeezing operator is obtained

$$H_{\text{eff}}=\xi_2(t)a^2+\xi_2(t)^{*}a^{+2} \tag{19}$$

which can squeeze an arbitrary state previously prepared in the cavity .

3 Discussion

In comparison with Ref. [5], we implement frequency conversions with a four-level atom and the advantage of our scheme is that we can get rid of the block from the dipole-forbidden atomic transition, so the microwave cavity is not necessary.

Now we give a brief discussion on experimental feasibility of the proposed scheme within cavity QED. The requirements of the scheme are: 1) negligible cavity attenuation during the whole preparation process; 2) no atomic spontaneous decay during the atom-cavity interaction.

For the generation of frequency down-conversion, the initial state of the atom is $|s\rangle$. For the sake of simplicity, we can set $|s\rangle$ as a Rydberg state which has the lifetime as long as 0.01 s[27]. The lifetime of a high-Q cavity, such as the superconducting cavity with low temperature, can reach the order of 0.01 s[27], which is much longer than typical atom-cavity interaction time of the order of 10^{-4} s[27]. In order to fulfill the requirements of the scheme, we choose $|g_1|=|g_2|=7\times10^5\ \mathrm{s}^{-1}$, $|\Omega_1|=|\Omega_2|=7\times10^7\ \mathrm{s}^{-1}$ and $|\Delta_1|=|\Delta_2|=7\times10^6\ \mathrm{s}^{-1}$. Then the effective interaction strength is about $|\xi_2|=3.5\times10^4\ \mathrm{s}^{-1}$ which is the same order as that in Ref. [5] and is larger than that in Ref. [8]. Considering the degenerate PDC process ($\omega_a=\omega_b$), we obtain the squeezing factor $\kappa=2|\xi_2|\tau\sim7$ with the atom-field interaction time about $\tau\sim2\times10^{-4}$ s, so the variance in the squeezed quadrature is $e^{-2\kappa}/4\sim2\times10^{-7}$, smaller than that in Ref. [8].

In summary, we have proposed a scheme to construct bilinear and quadratic Hamiltonians for frequency up- and down-conversions in cavity quantum electrodynamics (QED), which is based on the interactions of a single four-level atom simultaneously with two classical driving fields and a two-mode cavity. We decouple the atomic degrees of freedom from the cavity degrees of freedom and realize the frequency conversion for the cavity modes by initially preparing the atom in a suitable state.

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两模腔中的参量上转换和下转换

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摘　要：提出了一种通过建立双线性二次哈密顿量在量子腔中实现参量上转换和下转换的方案．通常在非线性过程中，介质本身不参与能量的净交换，但光波频率可以发生转换的作用称为参量转换作用．此方案建立在一个四能级原子同时与两经典场和两量子场相互作用的基础上，理论属于非线性光学四波混频范畴．将原子制备在合适的能级上，经典光场与相应的能级发生共振，而同时量子光场与相应的能级产生大失谐相互作用，在强相互作用区域内，原子和腔场失耦合，进而实现腔模的参量转换．根据所制备初始能级的不同以及光场激发能级的差异，分别实现了参量上转换和参量下转换．在利用参量下转换制备压缩算符后，对实验的可行性进行了讨论，并且给出了理论值．结果表明：在级联三能原子中采用一个级联双光子过程代替了原来的两个偶极禁戒跃迁间的经典驱动，可以保证高的不同频率之间的转换效率，并且用于光的量子操控和量子信息处理．

关键词：参量转换；腔量子电动力学