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Tunable white light cavity induced by interacting dark resonances

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ABSTRACT

We propose a scheme for a broadband optical cavity induced by interacting dark resonances in a Λ-type four-level atomic system. The interacting dark resonances leads to constructive interference for the nonlinear dispersion and destructive interference for the absorption between two electromagnetically induced transparency windows. The enhanced nonlinear anomalous dispersion is used to broaden the cavity linewidth. The simulation results show that the cavity linewidth could be widened more than one order of magnitude broader than an empty-cavity linewidth. Moreover, the cavity linewidth depends on the intensities and the detunings of coupling fields.

1. Introduction

Intracavity dispersion medium can modify properties of an optical cavity dramatically. Normal dispersion in an electromagnetically induced transparency (EIT) [1] window has been used to narrow a cavity linewidth [2,3]. While, if an anomalous dispersion medium is placed in a cavity, the changes of a round-trip phase shifts for different frequencies can be compensated for by the suitable phase shift generated via a frequency-dependent index of refraction. Then both high intensity buildup and large bandwidth can be easily achieved in an optical cavity, which is called a white light cavity (WLC) [4]. The performances of WLC with different anomalous dispersion transparency medium were compared [5], and multi-level systems were found to be suitable for a larger negative dispersion. WLC can be used for gravitational wave detectors (GWD) [6] and broadband optical communications [7]. In the frame of cavity quantum electrodynamics, WLC scheme is valuable for controlling light polarization rotation and switching [8].

Several WLC schemes have been explored for applications. Based on Raman coherence, anomalous dispersion between two gain lines was used to broaden the cavity linewidth [9]. Its noises and parameter deviations were later studied for precision measurements [10]. In this case, the cavity linewidth was limit, $\sim$20 MHz. An enhanced WLC via four-wave mixing (FWM) was studied considering the field propagation dynamics [11]. Its results show that in-medium dynamics counterintuitively lead to an enhancement of the cavity bandwidth, and the WLC linewidth is up to dozens of MHz. While, the conversion efficiency of FWM is a limiting factor for achieving WLC in this scheme. Also, a WLC was realized in a whispering gallery-mode resonator [12], which, however, depended on an effectively continuous-mode spectrum, and the input and output coupling was rather low.

A different mechanism to realize WLC is based on EIT. Intracavity EIT medium exhibits normal linear dispersion within the EIT window, while nonlinear dispersion is negative (anomalous dispersion) [13]. The dispersion slope of the total susceptibility changes to negative due to competing linear and nonlinear dispersions at approximate parameters, and this was used to broaden the cavity linewidth. Experimental results showed that the cavity linewidth became 28 MHz which is broader than its empty-cavity linewidth ($\sim$17 MHz) [14]. Based on the above EIT scheme, a WLC was demonstrated with a large coupling power and its linewidth becomes broader [15]. However, these studies are carried out in single-dark-resonance systems, so the large coupling power is required for the nonlinear dispersion.

It is well known that dark resonance is the basis of EIT and relative phenomena. Dark states will split when a coherent perturbation field is applied. This is a double-dark-resonance system [16] and was observed in cold [17] and hot atoms [18], respectively. Interaction of the dark resonances has been predicted [19] and demonstrated [20] to enhance Kerr nonlinearity. Giant Kerr nonlinearity with weak coupling power shows the superiority of a double-dark system to a single-dark system. But few works concern WLC schemes based on a double-dark-resonance system.

Here we predict that an enhanced nonlinear dispersion can be used to widen a cavity linewidth. Interacting dark resonances lead to a large Kerr nonlinearity of the system. The enhanced self-Kerr nonlinearity exhibits anomalous dispersion between two EIT

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windows, which can compensate for the phase shifts of different frequency components. Then the optical cavity may have large bandwidth and high transmission. The simulation shows that the WLC linewidth could be widened nearly 20 times broader than an empty-cavity linewidth. The peak value of transmission is up to 80% of the empty-cavity transmission. Both linewidth and transmission in the proposed scheme are superior to a single-dark-resonance system. Furthermore, the present scheme is a different mechanism from the previous schemes. The induced coherence of the system leads to quantum interference between two dark resonances, which contributes the above results. Previously we proposed a scheme for obtaining a tunable ultranarrow linewidth of a cavity with an atomic system [21], but the discussion was only in a linear regime. Here interacting dark resonances induces a large nonlinear dispersion, and we use the enhanced anomalous dispersion to broaden a cavity linewidth. The proposed scheme may have potential applications in high-sensitivity detection and broadband optical communications.

2. Model and theoretical analysis

The Λ-type four-level atomic system are shown in Fig. 1. In experiments, a possible energy level is easily found in the $5S_{1/2} \leftrightarrow 5P_{3/2}$ transitions of ^{87}Rb atoms. The levels ($5S_{1/2}$, $F=1$, $m=1$), ($5S_{1/2}$, $F=2$, $m=-1$) and ($5S_{1/2}$, $F=1$, $m=-1$) correspond to three low states $|1\rangle$, $|3\rangle$ and $|4\rangle$, respectively. The level ($5P_{3/2}$, $F=2$, $m=0$) corresponds to the excited state $|2\rangle$. A σ^- polarized probe field and a σ^+ polarized control field couple the transitions $|1\rangle \leftrightarrow |2\rangle$ and $|2\rangle \leftrightarrow |3\rangle$ with Rabi frequency Ω_p and Ω_c, respectively. A microwave field interacts with the $|3\rangle \leftrightarrow |4\rangle$ transition with Rabi frequency Ω_m. γ_{ij} denote longitudinal population decay rates from $|i\rangle$ to $|j\rangle$ $(i \neq j)$ and $\Gamma_{ij} = \sum_{l(l<i,j)}(\gamma_{il}+\gamma_{jl})/2$ are the dephasing rates. Similar four-level systems have been widely used to achieve slow light [22], enhancement of four- and six- wave mixing [23,24], light-matter entanglement [25], spatial vector solitons [26] and atomic localization [27,28], intracavity double dark states [29], etc.

In the interaction picture and after the rotating wave approximation, the Hamiltonian of the system is given by [19]

$$H = -\hbar[\delta_1(|2\rangle\langle 2| + |3\rangle\langle 3|) + (\delta_1 - \delta_3)|4\rangle\langle 4| + \Omega_p|1\rangle\langle 2| + \Omega_c|2\rangle\langle 3| + \Omega_m|3\rangle\langle 4|], \quad (1)$$

where $\Omega_j = E_j\mu_j/2\hbar$, $(j=p,c,m)$, $\delta_1 = \omega_p - \omega_{21}$ and $\delta_3 = \omega_m - \omega_{34}$ are the corresponding frequency detuning of the coupling fields. The control field resonantly couples the $|2\rangle \leftrightarrow |3\rangle$ transition. Place the atomic medium inside an optical cavity. The cavity field serves as the probe field. The response of atomic medium to an optical cavity is governed by atomic polarization

$$P = \varepsilon_0 \chi E_p, \quad (2)$$

where the total susceptibility $\chi = \alpha\rho_{21}$, and $\alpha = 2N|\mu_{12}^2|/(\varepsilon_0\hbar)$ with atomic density N. ρ_{21} is a total solution of the density matrix equations [30]

$$\partial\rho/\partial t = -i[H,\rho]/\hbar + L\rho, \quad (3)$$

and $L\rho$ are the relaxation terms. The cavity transmission can be described as [16]

$$S(\omega) = t^2/\{1 + r^2\kappa^2 - 2r\kappa\cos[\Phi(\omega)]\}, \quad (4)$$

where r and t are the reflectivity and the transmissivity of both the input and output mirrors, and $r^2+t^2=1$. The total phase shift $\Phi(\omega) = \omega/c(L + l\mathrm{Re}[\chi])$ and the absorption per round trip $\kappa = \exp\{-\omega l \mathrm{Im}[\chi]/c\}$. The real part of the atomic susceptibility brings dispersion and additional phase shift, and the imaginary part introduces absorption leading to the attenuation of the fields amplification. Of course, the solution of the cavity transmission can also be obtained under the small-gain approximation [31].

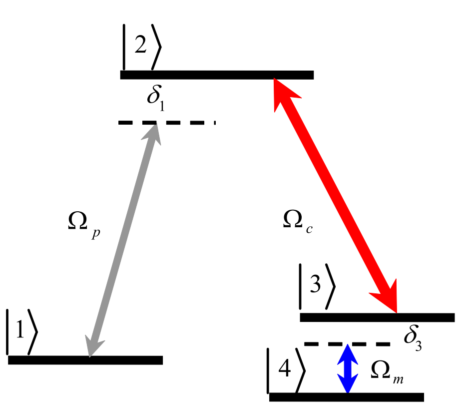

Fig. 1. Four-level atomic system with coupling scheme.

3. Results and discussions

Consider a 37.5-cm-long optical ring cavity and a 5-cm atomic vapor with density $N = 4 \times 10^{13}\,\mathrm{cm}^{-3}$. For simplicity, $\gamma_{21} = \gamma_{23} = \gamma_{24} = 2\gamma$, and all the parameters are scaled by γ. Fig. 2 shows the coherence term ρ_{21} and cavity transmission $S(\omega)$ under different conditions, which are based on the full solutions of Eq. (3). The intensity of cavity transmission is scaled by the output intensity of an empty cavity. When the control field is applied, a Λ-type EIT system is formed with the weak probe field by sharing an excited state. This is a single-dark-resonance system and one EIT window appears with normal dispersion. Under the perturbation of a microwave field, the dark state splits and two transparency windows appear [see Fig. 2(a1)]. The cavity transmission shows two symmetric transmission peaks [see Fig. 2(a2)]. The atomic system exhibits anomalous dispersion between two EIT windows. But the large anomalous dispersion is accompanied by a strong absorption, thus it is not fit for WLC. When increasing the intensities of the probe and the control fields, nonlinear effects emerge. The central absorption is depressed while remaining a large anomalous dispersion between two EIT windows (blue solid line in Fig. 2(b1)). Then a central transmission peak appears between two cavity transmissions [see Fig. 2(b2)]. With increasing the microwave-field detuning, (e.g. $\delta_3 = 1$), the anomalous dispersion appears in a wide frequency range and the left transmission peak becomes broad [see Fig. 2(c2)]. When $\delta_3 = 1.5$, the anomalous dispersion is extended over a wider frequency range. The cavity linewidth is much broadened [see Fig. 2 (d2)], which is the so-called WLC. The empty-cavity linewidth is ~ 3 MHz when $r = 0.9968$ according to [9,12]. Here, the WLC linewidth is broadened up to ~ 50 MHz, which is nearly 20 times broader than the empty-cavity linewidth. Also, Fig. 2 shows that the cavity linewidth depends on the intensity and detuning of the coupling fields, so a tunable WLC could be achieved.

We further examine the nonlinear susceptibility. The first- ($\chi^{(1)}$) and third- ($\chi^{(3)}$) order susceptibilities can be obtained by solving the Eq. (3), respectively.

$$\chi^{(1)} = \alpha B/(A - 3i\gamma B), \quad (5)$$

and

$$\chi^{(3)} = \chi^{(3)}_{dark} + \chi^{(3)}_{other}, \quad (6)$$

where

$$\chi^{(3)}_{dark} = \alpha(|\mu_{12}|^2/\hbar^2)\{\Omega_c^2\Omega_m^2(5\delta_1^2 - 3\delta_1\delta_3 - 2\delta_3^2 - 4\Omega_m^2)$$