Optics Communications 427 (2018) 363–368

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Hybrid transparency effect in the drop-filter cavity–waveguide system

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ARTICLE INFO

Keywords:
Electromagnetically induced transparency
Dipole induced transparency
Hybrid transparency

ABSTRACT

We theoretically investigate hybrid transparency effect, which incorporates both dipole-induced transparency (DIT) and all-optical electromagnetically induced transparency (EIT)-like effects, in the drop-filter cavity–waveguide system. It is shown that the hybrid transparency effect originates from not only destructive interference of the cavity fields but also interference between DIT and all-optical EIT-like effects, thus the disappearance and revival phenomena of transparency windows occur. Especially, the transmission amplitude of hybrid transparency effect is even larger than that of all-optical EIT-like effect in the case of large intrinsic loss of microcavity. Benefiting from the hybrid transparency effect, photonic Stern–Gerlach-like and Faraday rotation effects can be realizable in multiple regimes, which may be useful for hybrid quantum information processing with photon and solid state qubit.

1. Introduction

Electromagnetically induced transparency (EIT) effect [1], which was firstly found in the atomic system, is crucial for coherent manipulation of light. Up to now, the analog transparency effects have already been theoretically proposed and experimentally demonstrated in many other systems, e.g. quantum dots [2], superconducting circuits [3], metamaterials [4], nanoplasmonics [5], optomechanics [6] and all-optical coupled resonators [7–9]. Drop-filter cavity–waveguide system, which have been experimentally demonstrated in two-dimensional photonic crystal [10] and whispering-gallery microcavity [11–13], is also one of the most promising platforms for studying photon transport, quantum sensing and quantum information processing (QIP) etc. In Ref. [14], Waks and Vuckovic have proposed dipole induced transparency (DIT) effect in the drop-filter cavity–waveguide system. The distinct advantage of DIT effect is that it only requires large Purcell factor of cavity quantum electrodynamics (QED) system, thus allows the system work in the bad cavity regime, which greatly relaxes the experimental requirement of cavity QED system. DIT effect is feasible with present technology and has already been experimentally demonstrated in the photonic crystal system [15,16]. If we consider the polarization degree of freedom (DoF) of incident photon, the drop-filter cavity–waveguide system with dipole emitter can readily modulate both the amplitude and phase of incident photon. The amplitude modulation feature can be utilized to split polarized light beam, thus functions as polarized beam splitter or photonic Stern–Gerlach apparatus [17], which may be useful for generating spatial entanglement of photon and related QIP [18,19]. In the case of perfect or balanced transmission and reflection of incident photon, photonic conditional phase shift or photonic Faraday rotation effect [20,21] may be obtained, which can also be useful for QIP [22] and quantum computation [23,24]. On the other hand, all-optical EIT-like effect has also been theoretically investigated with cascaded resonators in the drop-filter cavity–waveguide system [25,26], then experimentally demonstrated [7–9]. The all-optical EIT-like effect can overcome much of the limitations on decoherence and bandwidth from atomic states for EIT, which may be useful for stopping and trapping light at room temperature.

The waveguide-based devices are convenient for on-chip integration and can also exhibit strong light–matter interaction [27], thus on-chip quantum circuits with solid state resonator and qubit are highly desirable for coherent manipulation of photon and QIP. Based on DIT [14] and all-optical EIT-like effects [25,26], we theoretically investigate hybrid transparency phenomenon in the drop-filter cavity–waveguide system. It is shown that the locations of hybrid transparency windows have obvious shifts and the full-widths at half maximum of the dip (FWHMs) of hybrid transparency windows are narrower than those of DIT and all-optical EIT-like effects. Moreover, the amplitude of hybrid transparency peak behaves as the property of collapse and revival with increasing Purcell factor and decreasing detuning of cavity resonance frequency, which cannot be explained within the framework of DIT

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https://doi.org/10.1016/j.optcom.2018.06.081
Received 27 February 2018; Received in revised form 18 June 2018; Accepted 28 June 2018
Available online 3 July 2018

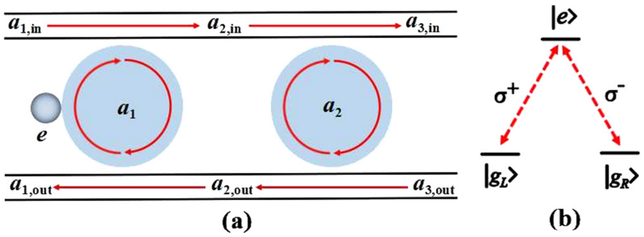

Fig. 1. (a) The schematic of hybrid transparency effect in the drop-filter cavity–waveguide system. (b) The energy-level configuration of dipole emitter. The transition $|g_{L(R)}\rangle \leftrightarrow |e\rangle$ is driven by left (right) circularly polarized light.

effect or all-optical EIT-like effect. In the case of large intrinsic loss of microcavity, the transmission amplitude of hybrid transparency effect is even larger than that of all-optical EIT-like effect. Therefore, the hybrid transparency effect originates from not only destructive interference of the cavity fields but also interference between DIT and all-optical EIT-like effects. Benefiting from the hybrid transparency effect, photonic Stern–Gerlach-like effect and photonic Faraday rotation effect can be realized in multiple regimes, which may be useful for QIP and quantum networks in the future. This paper is organized as follows. In Section 2, we present the theoretical model and its solution, then discuss the hybrid transparency phenomenon in Section 3. In Section 4, we investigate the potential application of hybrid transparency effect, e.g. photonic Stern–Gerlach-like effect and photonic Faraday rotation effect. Finally, we briefly discuss the feasibility of hybrid transparency effect.

2. The model and solution

The schematic of hybrid transparency effect is illustrated in Fig. 1(a), where two microcavities 1 and 2 with single modes a_1 and a_2 are evanescently coupled to two drop-filter waveguides. The dipole emitter with transition frequency ω_a is evanescently coupled to the first microcavity, and their interaction is descried by the Jaynes–Cummings model Hamiltonian. The Heisenberg–Langevin equations of cavity modes are ($\hbar = 1$)

$$\frac{da_1(t)}{dt} = -i(\omega_1 - \omega_p)a_1(t) - \frac{\kappa_1 + \kappa_2 + \kappa_0}{2}a_1(t) - g\sigma_-(t) - \sqrt{\kappa_1}a_{1,in}(t) - \sqrt{\kappa_2}e^{i\phi_1}a_{2,out}(t) - \sqrt{\kappa_0}e_{1,in}(t), \tag{1}$$

$$\frac{da_2(t)}{dt} = -i(\omega_2 - \omega_p)a_2(t) - \frac{\kappa_1 + \kappa_2 + \kappa_0}{2}a_2(t) - \sqrt{\kappa_1}a_{2,in}(t) - \sqrt{\kappa_2}a_{3,out}(t) - \sqrt{\kappa_0}e_{2,in}(t), \tag{2}$$

where ω_p, ω_i are the frequency of input field and the central frequencies of two microcavities respectively. κ_i is the cavity–waveguide coupling strength, and κ_0 is the intrinsic loss of microcavity. $a_{i,in}$ and $a_{i,out}$ describe the input and output fields of ith microcavity. ϕ_1 denotes phase delay along the waveguides between microcavities 1 and 2, and it determines the indirectly coupling strength of adjacent microcavities [28,29]. The asymmetric Fano lineshape can be obtained for $\phi_1 \neq m\pi/2$ with m being an integral number [28,29], and here we only consider $\exp(i\phi_1) = 1$ by choosing appropriate distance of microcavities as that in the all-optical EIT-like effect [26]. g and σ_- are the vacuum Rabi frequency and lower operator of dipole emitter. $e_{i,in}(t)$ is the noise input operator of ith microcavity which preserves the canonical commutation relation. The motion equation of dipole lower operator is

$$\frac{d\sigma_-(t)}{dt} = -i(\omega_a - \omega_p)\sigma_-(t) - \frac{\gamma_a}{2}\sigma_-(t) - ga_1(t)\sigma_z(t) + \sqrt{\gamma_a}\sigma_z(t)b_{in}(t), \tag{3}$$

where γ_a and $b_{in}(t)$ are spontaneous emission rate of dipole emitter and its noise input operator. In what follows, we consider the weak excitation limit [30], thus the dipole emitter is always in its ground state, which allows us to replace dipole population operator with its expectation value $\langle\sigma_z\rangle \approx -1$. Furthermore, we assume that the external noise input fields of dipole emitter and microcavities are in the vacuum state and the contributions of noise input operators are negligible (i.e., $\langle b_{in}(t)\rangle = 0, \langle e_{1,in}(t)\rangle = \langle e_{2,in}(t)\rangle = 0$). The output fields into the waveguides are related to the input fields by the input–output relations [31]

$$a_{2,in}(t) = a_{1,in}(t) + \sqrt{\kappa_1}a_1(t), \tag{4}$$

$$a_{3,in}(t) = a_{2,in}(t) + \sqrt{\kappa_1}a_2(t), \tag{5}$$

$$a_{1,out}(t) = a_{2,out}(t) + \sqrt{\kappa_2}a_1(t), \tag{6}$$

$$a_{2,out}(t) = a_{3,out}(t) + \sqrt{\kappa_2}a_2(t). \tag{7}$$

We assume that a weak monochromatic field with frequency ω_p input from the left port of upper waveguide as shown in Fig. 1(a), and the input fields from other ports of waveguides are discarded. After neglecting the contribution of $a_{3,out}(t)$, we can obtain the output fields into the waveguides as follows

$$a_{3,in}(t) = \{1 + \frac{\kappa_1[(i\Delta_1' - \frac{\kappa}{2} + \kappa_1) + (i\Delta_2 - \frac{\kappa}{2} + \kappa_2)]}{(i\Delta_1' - \frac{\kappa}{2})(i\Delta_2 - \frac{\kappa}{2}) - \kappa_1\kappa_2}\}a_{1,in}(t), \tag{8}$$

$$a_{1,out}(t) = \frac{\sqrt{\kappa_1\kappa_2}[(i\Delta_1' - \frac{\kappa}{2} + \kappa_1) + (i\Delta_2 - \frac{\kappa}{2} + \kappa_2)]}{(i\Delta_1' - \frac{\kappa}{2})(i\Delta_2 - \frac{\kappa}{2}) - \kappa_1\kappa_2}a_{1,in}(t), \tag{9}$$

where $\kappa = \kappa_0 + \kappa_1 + \kappa_2$, $i\Delta_1' = i\Delta_1 + g^2/(i\Delta_a - \gamma_a/2)$, $\Delta_i = \omega_p - \omega_i$ and $\Delta_a = \omega_p - \omega_a$. Analog to the double-sided microcavity, we denote the output fields into upper and lower waveguides as transmission and reflection fields respectively, thus can obtain the transmission coefficient $t = a_{3,in}(t)/a_{1,in}(t)$ and reflection coefficient $r = a_{1,out}(t)/a_{1,in}(t)$. We must point out that the same transmission and reflection coefficients will be obtained if the incident photon inputs from the right port of upper waveguide. In other words, the system is reciprocal when the phase delay along the waveguides satisfies the condition $\exp(i\phi_1) = 1$. We assume that two microcavities have equal coupling rates with the waveguides (i.e., $\kappa_1 = \kappa_2$), which is known as the critical coupling condition. In this case, the transmission and reflection coefficients are

$$t = \frac{1}{1 - \kappa_1[(i\Delta_1' - \kappa_0/2)^{-1} + (i\Delta_2 - \kappa_0/2)^{-1}]}, \tag{10}$$

$$r = \frac{\kappa_1[(i\Delta_1' - \kappa_0/2)^{-1} + (i\Delta_2 - \kappa_0/2)^{-1}]}{1 - \kappa_1[(i\Delta_1' - \kappa_0/2)^{-1} + (i\Delta_2 - \kappa_0/2)^{-1}]}. \tag{11}$$

3. Hybrid transparency effect

In the following, we investigate the transmission properties of incident field from the left port of upper waveguide as shown in Fig. 1(a), and the numerical calculation is based on Eqs. (10) and (11). We consider the case where dipole emitter is resonant with the first microcavity (i.e., $\omega_1 = \omega_a$) and the central frequencies of two microcavities are assumed to satisfy $\omega_2 - \omega_1 = \delta = \kappa_1/2$. The losses of microcavities to waveguides are far larger than their intrinsic loss, thus it is reasonable of considering the overcoupling regime $\kappa_1 \gg \kappa_0$, where the factor of 10^3 decrease in the quality factor relative to the original microcavity can be realizable (i.e., $\kappa_0 \approx 10^{-3}\kappa_1$) [11]. The dipole–microcavity coupling strength and dipole decay rate $(g, \gamma_a) = (0.33, 10^{-3})\kappa_1$ are taken into account [14]. In Fig. 2(a), it is shown that there are two sharp transparency windows (red solid) which incorporate both DIT (black dashdotted) and all-optical EIT-like effects (blue dotted). Compared with transparency windows in the DIT and all-optical EIT-like effects, the locations of transmission peaks, which are originally at $\omega_p - \omega_1 = 0$ and $\omega_p - \omega_1 = \delta/2$, have obvious shifts to $\omega_p - \omega_1 = (\delta - \sqrt{\delta^2 + 8g^2})/4$ and $\omega_p - \omega_1 = (\delta + \sqrt{\delta^2 + 8g^2})/4$ respectively. In the bad cavity limit $(\kappa_1, \delta \gg g)$, the locations of transmission peaks are $\omega_p - \omega_1 = g^2/\delta$ and