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All-optical analog to electromagnetically induced transparency effects for multiple wavelengths in a silicon photonic crystal coupled cavity system

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ABSTRACT

We design and theoretically study the all-optical analog to electromagnetically induced transparency (EIT) effect in a system consisting of two heterojunction cavities and one waveguide in a silicon photonic crystal slab with a triangular lattice. Multiple modes with a high Q_{int}/Q_c ratio are found in both cavities. By tuning the resonance difference and phase difference between cavities, EIT-like phenomena for two modes at different wavelengths are found. Our analyses show that optical delays of 0.34 and 0.20 ns are realized for each optical EIT peak, thereby benefiting further research and applications, such as multiple-wavelength switches, optical buffer devices, and signal processing. The relationship between the characteristics of the optical EIT-like peak and several parameters is investigated, and the results can provide a reference for future experiments. The 3D finite-difference time-domain method is used to analyze the field distribution in the process.

1. Introduction

The all-optical analog to electromagnetically induced transparency (EIT) effect has attracted much attention and brought many applications in various fields [1–11]. Compared with EIT in atomic systems [12], operating frequencies are no longer limited to specific atomic transitions in such systems. Moreover, given that strict conditions, such as low temperature and intricate devices, are avoided, this effect is more flexible and advantageous in practical photonic applications. Many theoretical and experimental results have shown that this EIT-like effect can be realized in both coupled whispering gallery mode resonators, such as ring resonators [1–4] and fused-silica microspheres [5], and standing wave resonators, such as coupled photonic crystal cavities [6–10] and plasmonic systems [11]. For optical EIT-like systems, the transparency peak arises from coherent interference between two resonant modes with different optical pathways. The transparency window with high transmission that appears between two dips in the transmission spectrum can work as a narrow optical filter [7]. Moreover, slow group velocities and optical delay are observed in such systems [2–6,10], providing great significance for applications toward on-chip optical trapping and storage of light.

Photonic crystal cavities have become the focus of recent studies because of their photonic band gap effect and relatively high-quality factors (Q) [13–16]. All-optical analog to EIT has been experimentally demonstrated in coupled photonic crystal cavity systems, and an optical delay of ~20 ps has been obtained [8]. However, 20 ps is not long enough for further applications, such as photon pulse trapping and light storage. Considering that the optical delay of an EIT-like system is highly related to cavity quality factors as well as the subtle change of wavelength detuning and phase difference detuning between cavities, new designs that support longer optical delay should be studied. Moreover, the EIT-like effect has been reported only for one mode in two cavities side-coupled with one waveguide system. Although previous works have used cascaded systems to support more modes [1,8], these systems are complex and detrimental for integration.

In this paper, we propose a coupled resonator system that consists of two cavities and one waveguide in a 2D photonic crystal slab with a triangular lattice. In our design, heterojunction cavities with intrinsic quality factors (Q_{int}) as high as $\sim 6.4\times 10^6$ are adopted. Coupling quality factors (Q_c) are also calculated through FDTD simulations. Two dominant resonant modes are found in each cavity, and each mode gives a high Q_{int}/Q_c ratio. Particularly, EIT-like phenomena for these two modes at different wavelengths are found through cavity resonance tuning and phase tuning. Furthermore, the EIT-like peaks are sharp and correspond to considerable optical delay, which has important implications for multiple-wavelength filter and optical buffer applications. In view

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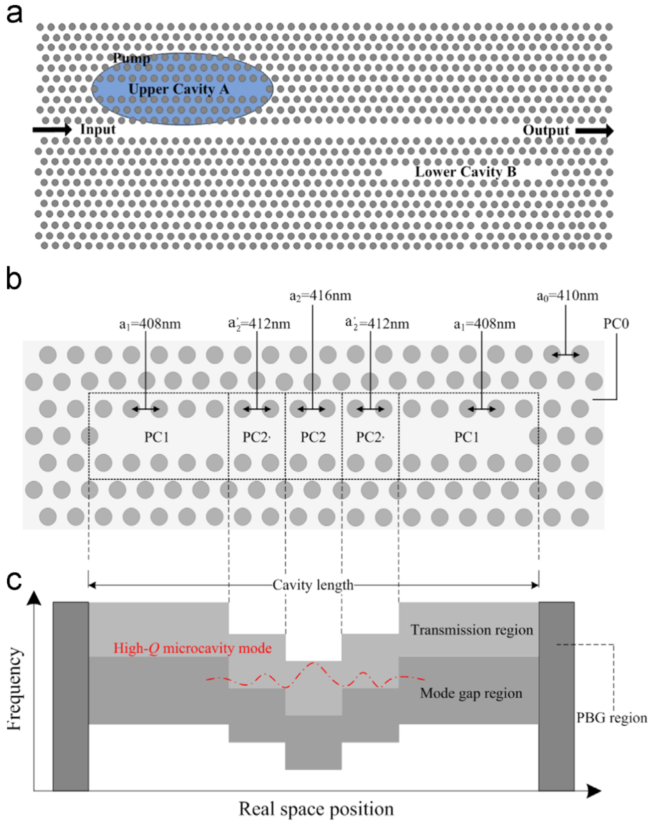

Fig. 1. (a) Schematic of EIT-like system including waveguide side-coupled to two cavities. The blue region indicates where the index is tuned. (b) Top view of two-step junction heterojunction cavity structure. Four PC regions with different lattice constants are found along the x-direction. The lattice constant changes only in the black dotted line frame region. (c) Band diagram of cavity along Γ–K direction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of all these, we argue that this system is a good candidate for compact devices in photonic integration.

This paper is arranged as follows. Section 2 describes the layout of the photonic structure for the EIT-like effect and analyzes the modes therein. Section 3 presents the related theory briefly and discusses the relation between the EIT-like peak characteristics and other parameters. Section 4 demonstrates the EIT-like effects for two modes at different wavelengths. Finally, some conclusions drawn from previous sections are provided in Section 5.

2. Design and analysis

Our EIT-like system [Fig. 1(a)] consists of one photonic crystal waveguide and two side-coupled cavities. The whole photonic crystal structure is designed on an air-bridged silicon slab. The thickness of the slab is $0.6a_0$, and the air hole radius is $r=0.29a_0$. Two-step heterojunction cavities are used to suppress the radiation mode field for high intrinsic quality factors [15]. Fig. 1(b) shows the detailed design of the cavities.

As shown in Fig. 1(b), the cavity has four lattice constants a_0, a_1, a_2', and a_2 along the x-direction in different regions marked PC0, PC1, PC2', and PC2. The lattice constant in the y-direction is $\sqrt{3}a_0/2$. Thus, the cavity is divided into five parts with 15 air holes missing in all. We change lattice constants only within a small black dotted line frame region. In this way, when a coupling waveguide exists outside the region, the transmission property of the waveguide is only slightly affected. The photonic crystal coupling waveguide is formed by filling one row of air holes along the Γ–K direction. Two cavities are arranged along the side of the waveguide with an optimized distance of three rows of air holes.

To obtain a precise and visualized result and ensure that the cavities operate in an over-coupled regime, the 3D FDTD method is used to analyze the cavity structure in Fig. 1(b). For the simulations, the refraction index of the silicon slab is set to 3.4. Mesh order is set to $a_0/20$, which should be small enough to obtain reliable results. The perfectly matched layer condition is adopted, and the calculating region is chosen as $25\times 7a_0$ along the x- and y-directions. Because the lattice constant varies along the x-direction, the transmission and mode gap frequencies vary [Fig. 1(c)]. Consequently, the modes are perfectly restricted in the cavity and show high unloaded intrinsic quality factors (Q_{int}) [13–15]. However, loaded Q_{int} in the presence of the coupling waveguide slightly varies from unloaded Q_{int} because of the effective refractive index change of the cavity with the introduction of the waveguide. In such cases, we can calculate the Q_{int}^{-1}/Q_c^{-1} ratio by measuring the in-plane and out-of-plane power leaks from the Poynting-vector integration [17,18]. The total quality factors (Q_{tot}) can be calculated with the structure containing the waveguide. Combined with the relation $Q_c^{-1}=Q_{tot}^{-1}-Q_{int}^{-1}$, Q_c and Q_{int} in the loaded cases can be obtained. Table 1 shows the resonant wavelengths of multiple modes in the cavity.

As shown in Table 1, three dominant resonant modes are found in the cavity, and all of them show relatively high Q_{int}. Resonant modes 1 and 2 show a high Q_{int}/Q_c ratio, which satisfies the criteria that the system operates in the over-coupled regime with vertical radiation loss well suppressed for in-plane interference. Compared to the non-heterojunction system in [8–10], our system provides a high Q_{int}/Q_c ratio, a figure of merit to achieve a reasonable EIT-like peak. Q_{int} scales because of the introduction of the heterojunction. Meanwhile, given that an evident EIT-like behavior is usually judged by $\lambda/Q_{int} \ll \Delta\lambda \ll \lambda/Q_c$ [20], high Q_c requires us to give finer resonance tuning for an obvious transparency peak. However, in spite of high Q_{int} and Q_{int}/Q_c ratio, mode 3 is unsuitable for an EIT-like effect because it is not supported in the photonic crystal waveguide. Thus, mode 3 is not a part of the scope of our consideration. Fig. 2 shows the field profile and k-space distribution of modes 1 and 2.

In our design of the whole system, the center-to-center separation (L) between the cavities is finally chosen as $26a_0$, which gives a remarkable EIT-like effect during simulations because the phase difference ϕ between cavities is close to $n\pi$ (n is an integer here) at such a distance, satisfying the condition of forming a Fabry–Pérot resonance (round-trip phase difference between cavities $2\phi\sim 2n\pi$). In fact, the final EIT-like spectral line is sensitive to ϕ, which is discussed in Section 3.

Table 1
Resonant wavelengths of multiple modes in two-step heterojunction cavity. The second column is the resonant wavelengths of each cavity; the following columns show the Q_{int}, Q_{tot}, and Q_c and the ratio of Q_{int}/Q_c. The wavelength detuning column shows the range of wavelength detuning between the two cavities for an obvious EIT-like observation.

Mode label	λ (nm)	Q_{int}	Q_{tot}	Q_c	Q_{int}/Q_c	Wavelength detuning $\lambda_A-\lambda_B$ (pm)	EIT-like (yes or no)
1	1544.38	565,067	15,841	15,917	35.5	$2.73\ll\lambda_A-\lambda_B\ll 97.03$	Yes
2	1548.88	6,408,309	45,449	45,774	140.0	$0.24\ll\lambda_A-\lambda_B\ll 33.84$	Yes
3	1552.18	5,811,172	46,940	47,322	122.8	$0.27\ll\lambda_A-\lambda_B\ll 32.80$	No