Effect of electromagnetically induced transparency on spectrum of defect modes of photonic crystal

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EFFECT OF ELECTROMAGNATICALLY INDUCED TRANSPARENCY ON SPECTRUM OF DEFECT MODES OF PHOTONIC CRYSTAL

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ABSTRACT

The effect of electromagnetically induced transparency on the spectrum of defect modes of one-dimensional photonic crystal is discussed theoretically. Narrowing of defect mode linewidth is predicted due to nonabsorbing highly dispersive medium in defect layer.

Keywords: photonic crystal, defect mode, photonic band gap, localized mode, electromagnetically induced transparency.

1. INTRODUCTION

Photonic crystals (PhCs) are naturally or artificially structured inhomogeneous materials in which the refractive index varies periodically over a length scale comparable to optical wavelengths. There is large interest to investigating of PhCs because they offer tremendous possibility to manipulate of the light flows. One of the most striking features of PhCs is associated with existence of frequency ranges over which ordinary linear propagation is forbidden. These ranges are called the photonic band gap (PBG) [1, 2]. PBG lend themselves to numerous applications in linear, nonlinear and quantum optics. With their remarkable capabilities of localizing and guiding radiation, PhCs can be used to create high-Q micro- and nanocavities [3, 4], as well as narrow waveguides [5], and microlasers [6]. They have opened a new chapter in nonlinear optics named the nonlinear optics under ultralow energy level [7]. The dispersive properties of PhCs can be exploited for manipulating of group velocity of light and optical pulse shaping and compression [8], negative refraction [9] and superprism effects [10].

A very interesting situation arises when foreign atoms or ions (dopants) with transition frequencies within the PGB are implanted in the PhC [11, 12]. A system in which an optical resonance has its frequency close to a Bragg frequency is often called a resonant photonic crystal (RPC) or resonant photonic bandgap structure. In this class we have also multiple semiconductor quantum-well structures that have an exciton resonance close to a Bragg frequency [13 - 15] and optical lattices of absorbing atoms [16]. An important potential of RPC is stopping, storing and releasing of light [15, 17].

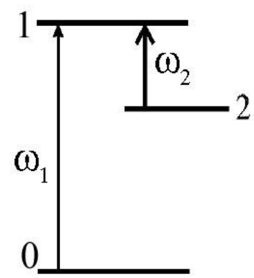

Fig. 1 Schematic diagram of the three-level Λ atom. The weak probe and strong-coupling fields have the frequencies ω_1 and ω_2, respectively. ω_1-ω_2~ω_{20}; ω_{20} is the frequency of a forbidden transition |2>-|1>.

Materials and systems that support electromagnetic-induced transparency (EIT) are another class of materials having unique properties [18]. A typical EIT system consists of a weak probe field and a strong coupling field resonantly

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interacting with a three-level medium as shown in Fig.1. Here the levels |0> and |2> are the ground and metastable states, respectively. The state |0> is essentially the only populated level. The transition |0>-|1> is coupled to the weak probe field with center frequency ω_1 and wavenumber k_1. Respectively the transition |2>-|1> is coupled to an external drive field with frequency ω_2 and wavenumber k_2. Under resonance conditions ω_1-ω_{10}=0 and ω_2-ω_{12}=0 the medium becomes nonabsorbing and highly dispersive for probe (the effect of EIT). This effect has attracted a great attention due to unusual optical properties and potential applications (see, e.g., the recently review [19] and references there). For example, EIT was used to achieve ultraslow group velocity of light [20], to increase nonlinear optical processes [21], and for a storage and retrieval of light pulses [22], using thermal gasses, Bose-Einstein condensates and as well as solid-state media. EIT medium combined with a cavity can lead to a number of interesting linear and nonlinear effects. Particularly, it is demonstrated substantial narrowing of the transmission curve of a macroscopic ring cavity using EIT [24-26]. A combination of the EIT medium with the photonic band gap structures opens new possibilities for manipulating of light and PhCs characteristics as well [7, 27-32].

Under consideration of interaction of light with atoms in PhC it is necessary to take into account the fact that the modes of PhC are the quasistanding-waves and there coupling with atoms is position dependent. Therefore in the most of all the above studies it is supposed, that a range occupied with doped atoms has extent much less wavelength of light. For instance, in [27, 28] PhC microcavity is doped with a single EIT atom. The effect of the mode structure of PhC on interaction with atoms is the fundamental and practical significance. This motivates for further study of the optical properties of PhC combined with the EIT-medium.

The aim of this paper is to investigate a transmission spectrum of one-dimensional PhC with a defect layer filled with EIT medium. As distinct from others paper, in our model we take into accounting the spatial distribution of the coupling and probe electric fields inside the photonic crystal structure.

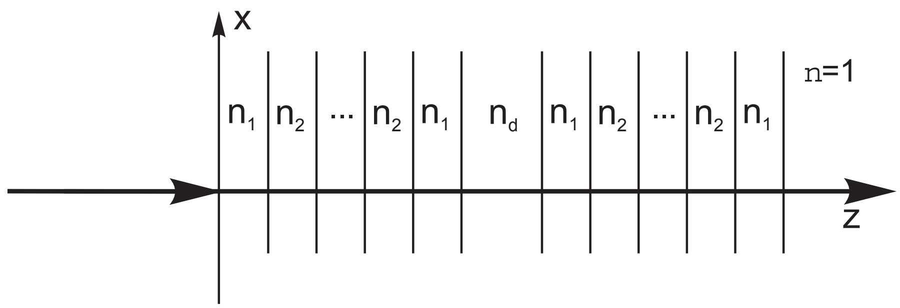

Рис. 2. Schematic of one-dimensional photonic crystal with a defect layer.

MODEL AND APPROXIMATIONS

The structure of the PhC under consideration is $(HL)^M H\ D\ H(LH)^M$ as shown in Fig. 2. Here H and L stand for the different dielectric layers with high and low refractive index n_1 and n_2 and thicknesses d_1, d_2; M is the number of bilayers; D is the defect layer with refractive index n_D and thickness d_D. The defect layer is doped with three-level atoms in Λ-configuration (Fig. 1) with the resonance frequencies of transitions ω_{10} and ω_{12}. We assume that the atoms are immovable and don't interact with each other. Parameters of the PhC are chosen thus, that there are two defect modes within stop-band with resonance frequencies ω_a and ω_b. Spectra of defect modes overlap with atomic transitions lines and $\omega_a=\omega_{10}$, $\omega_b=\omega_{12}$. The spectral widths of modes are much greater than the widths of the atomic resonances.

Two plane monochromatic light waves with frequencies ω_1 (the weak probe field) and ω_2 (the strong coupling field) fall normally onto the PhC and propagate along an axis Z (z=0 corresponds to the boundary of the first layer). We assume that the amplitude of the probe field E_1 is much smaller in comparison with the amplitude E_2 of the coupling field. A wave equation for the probe and coupling fields propagating in spatially modulated 1D medium is (in frequency domain)

$$\frac{d^2}{dz^2}E_{1,2}+\frac{\omega_{1,2}^2 n^2(z,\omega)}{c^2}E_{1,2}=0\,, \tag{1}$$

where $\omega_{1,2}$ are the frequencies of propagating fields; c is the velocity of light in vacuum; n is the refractive index for probe and coupling fields. We assume that the refractive indexes for the probe and coupling field are equal n_1 and n_2 in each layer, i.e. we shall neglect dispersion of a medium.

For the EIT-medium the refractive index is $n_p = n_D = 1+2\pi\chi$, where the susceptibility χ for the weak probe field in presence of the strong coupling field [18] reads

$$\chi = \chi_0 N \frac{\Gamma_{10}\Delta_{20}}{\Delta_{20}\Delta_{10} + |G_2(z)|^2}, \tag{2}$$

where $\Delta_{10}=\omega_1-\omega_{10}-i\Gamma_{10}$, $\Delta_{20}=\omega_1-\omega_2-\omega_{20}-i\Gamma_{20}$, Γ_{10} and Γ_{20} are the half-width of respectively transitions; $G_2(z)$ is the Rabi frequency of the coupling field; N is atomic number density; χ_0 is the one-photon resonance susceptibility of the atom for the probe field in absence of the coupling field. When the EIT-medium is absent in the defect layer $n_D=1$ for each field.

Figure 3 shows the imaginary and real part of the susceptibility χ of an ensemble of stationary (immobile) atoms for the case of the resonant coupling field ($\omega_2 - \omega_{12} = 0$) as a function of the probe field detuning ($\Delta\Omega = \omega_1 - \omega_{10}$) from resonance. Imaginary part of the susceptibility undergoes destructive interference in the region of resonance, i.e., the coherently driven medium is transparent for the probe field, while real part of the susceptibility has a normal dispersion in a region of low absorption, the steepness of which is controlled by the coupling-laser strength. It can be very steep for low values of the drive laser coupling.

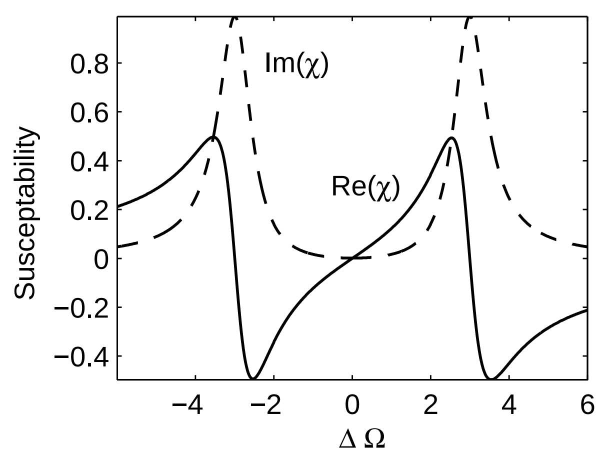

Fig. 3. The EIT susceptibility as a function of the frequency detuning of the probe field relative to atomic resonance frequency ω_{10} for the resonant coupling field. Imaginary part of χ defines absorption and real part of χ determines the refractive properties of the medium. in terms of

The fields in the j-th layer are a superposition of fundamental solutions of Eq. (1)

$$E_j(z) = A_j e^{is_j z} + B_j e^{-is_j z}. \tag{3}$$

Here A_j and B_j are the amplitudes of the forward and backward waves, $s_j = kn_j$, $k = 2\pi/\lambda$, n_j is the refractive index of j-th layer.

It is convenient to calculate amplitudes of the forward A_j and backward B_j waves, using the recurrence relation method [33]. For this purpose, we shall divide all layers into a large number M of sublayers where the field E_m can be considered as a constant. Using the conditions of continuity for tangential components of electric and magnetic fields at the interface between sublayers with numbers m and $m+1$ we receive a set of equations:

$$A_m + B_m = g_{m+1}^{-1} A_{m+1} + g_{m+1} B_{m+1} \tag{4}$$

$$s_m(A_m - B_m) = s_{m+1}(g_{m+1}^{-1}A_{m+1} - g_{m+1}B_{m+1}) \,. \qquad (5)$$

Here $g_m = \exp(is_m t_m)$, t_m is the thickness of the m sublayer.

From Eqs. (4)-(5) we obtain a recurrence formula to calculate amplitudes A_m and B_m in the arbitrary layer

$$A_{m+1} = A_m \frac{1+R_m}{g_{m+1}^{-1} + g_{m+1}R_{m+1}} \,, \qquad (6)$$

where

$$R_m = \frac{B_m}{A_m} = \frac{r_m + g_{m+1}^2 R_{m+1}}{1 + r_m g_{m+1}^2 R_{m+1}} \,, \qquad (7)$$

$$r_m = \frac{s_m - s_{m+1}}{s_m + s_{m+1}}$$

The recursion formula (7) connects the reflective index R_m of the m-th layer with that of the layer with number $m+1$. With the help of the recursion formula (7) all R_m are obtained, beginning from the right boundary PhC with the account of boundary condition R_{M+1}. After the finding of all reflective indices R_m, the Eq. (6) is solved beginning from the left boundary of PC. The amplitudes of backward waves are found from formula

$$B_m = A_m R_m \,. \qquad (8)$$

These recurrent relations are exact equations due to we does use any approximation. The coefficients of transmission T, reflection R and absorption A are defined by formulas

$$T = \left|\frac{A_{M+1}}{A_0}\right|^2, \quad R = \left|\frac{B_0}{A_0}\right|^2, \quad A = 1 - T - R \,. \qquad (9)$$

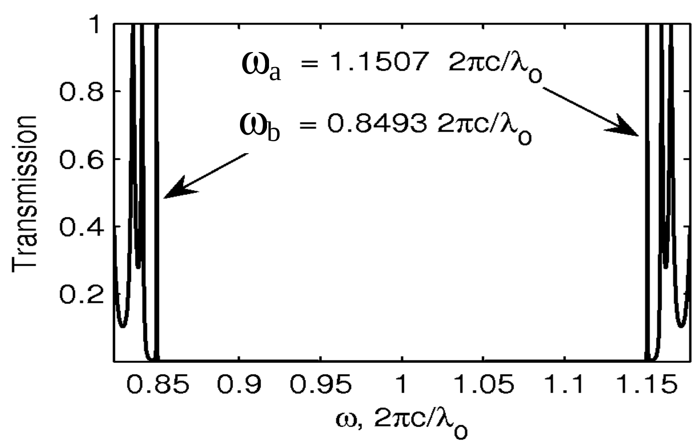

Fig. 4. The transmission spectrum of photonic crystal with the structure $(HL)^{20}H\,D\,H(LH)^{20}$. $n_1d_1=n_2d_2=\lambda_0/4$, $n_Dd_D=3\lambda_0/4$, $n_D=1$, λ_0 is wavelength for first band gap center, ω is measured in units of $2\pi c/\lambda_0$.

3. RESULTS

Using formulas (6)-(9) we first calculate the transmission spectrum of PhC and a spatial distribution of the probe and coupling fields within PhC when the EIT-medium in the defect layer is absent. The parameters of PhC were chosen to obtane two modes in the stop-band. The calculated transmission spectrum of PhC with two defect modes is shown in Fig.4 (without EIT medium in defect layer). It demonstrates two sharp transmission peaks near edges of the band-gap with resonance frequencies ω_a and ω_b. Further we shall assume, that the absorption spectra of Λ-atoms are covered with these defect modes and $\omega_a=\omega_{10}$, and $\omega_b=\omega_{12}$.

The spatial distribution of the probe and coupling fields within PhC at the frequencies corresponding to maxima of transmission of defect modes are shown in the Fig. 5. The figure shows that greatly enhanced light fields at $\omega_a=\omega_1$ and $\omega_b=\omega_2$ are mightily localized near the defect layer. These results indicate that PhC can be used to greatly enhance light-matter interactions even when the optical response of the individual molecules is weak.

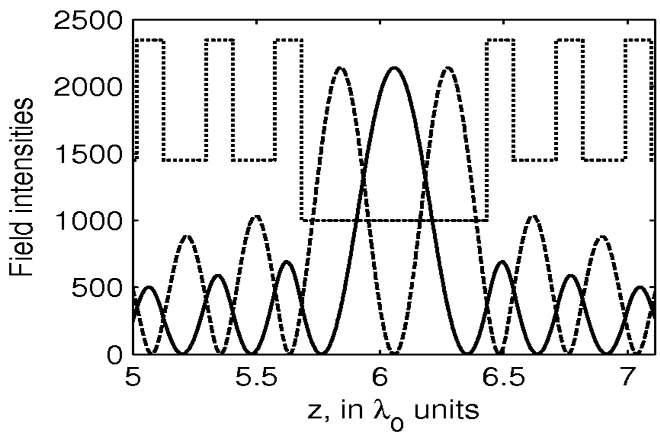

Fig. 5. A space distribution of intensity of the probe (*dash line*) and control (*solid line*) fields normalized to that of the input wave. The frequencies ω_1 and ω_2 coincide with maximum of the defect modes. *dots line* – refractive index (schematically)

The Fig. 6 shows results of model calculations of the PhC transmission at the frequency of the probe field for three different cases.

1) EIT medium in the defect layer is absent (n_D=1 for the probe and coupling fields). Well known contour of the transmission of light is observed in this case (Fig. 6a). Defect mode has very narrow transmission peak in a background of strong reflection, which is similar to the transmission peak in a completely absorbed background as in EIT. It is expected that at the peak there is a large reduction in the light group velocity as in the case of EIT.

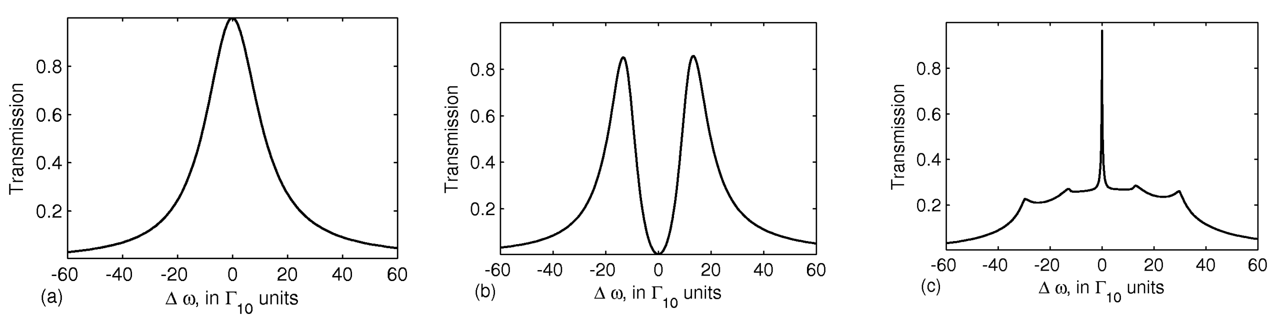

Fig. 6. Transmission spectra of PhC for the probe wave. a) EIT-medium is absent in PhC; b) PhC with EIT-medium, the control field is switched off; c) EIT medium is present at defect layer of PhC. The Rabi frequency of the coupling field in maximum equals to 3 cm^{-1}. $\Delta\omega=\omega_1-\omega_{10}$, $\omega_{10}=\omega_a$, $\omega_{12}=\omega_b$, $\Gamma_{10}/\Gamma_{20}=100$.

2) The defect layer is filled with EIT medium and the control field is switched off. Here two peaks of the transmission are observed (Fig. 6b). Such a behavior of defect mode is a consequence of the linear absorption and dispersion of the resonant medium imbedded into the defect [12, 13]. The effect is the same as in the case of normal-mode-coupling semiconductors microcavities [14]. The spatial distribution of the light intensity within the PhC at the frequencies corresponding to maxima of transmission is identical l to the case without dispersion.

3) The transmission spectrum of PhC for the probe field in EIT conditions is shown in Fig. 6c. The narrow peak against a background of wide line is determined by nonabsorbing highly dispersive EIT medium. Spectral width of this peak is much less, than for usual defect mode. In calculation we assume the coupling field is given with space distribution within PhC as shown in Fig. 5, as the EIT condition implies there is no population in the upper state |1>. Let's also note that the intensity necessary for observation EIT in PhC can be much less than in case of a free cell due to the localization effect of light into the defect layer.

4. CONCLUSIONS

We have analyzed the transmission spectrum of one-dimensional photonic crystal containing the EIT medium as the defect layer. The theoretical model was used to take into account the spatial distribution of the control field. The EIT essentially reduces the spectral linewidth of the defect mode. The photonic crystal combined with EIT medium allows observing EIT at lower intensity of the control field than in a case of free cell. The standing of a line can be drived, changing frequency of the coupling field. A combination of PhCs with solid-state EIT media is especially perspective, as the atomic transitions interacting with the coupling field have the typically weak oscillator strengths.

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