Dimension-sensitive optical responses of electromagnetically induced transparency vapor in a waveguide

Jian Qi Shen[1,*] and Sailing He[2]

[1]*Centre for Optical and Electromagnetic Research, Joint Research Centre of Photonics of the Royal Institute of Technology, Stockholm, Sweden and Zhejiang University, East Building No. 5, Zijingang Campus, Hangzhou 310058, People's Republic of China*

[2]*Division of Electromagnetic Theory, Alfvén Laboratory, Royal Institute of Technology, S-100 44 Stockholm, Sweden*

(Received 16 July 2006; revised manuscript received 23 October 2006; published 28 December 2006)

A three-level EIT (electromagnetically induced transparency) vapor is used to manipulate the transparency and absorption properties of the probe light in a waveguide. The most remarkable feature of the present scheme is such that the optical responses resulting from both electromagnetically induced transparency and large spontaneous emission enhancement are very sensitive to the frequency detunings of the probe light as well as to the small changes of the waveguide dimension. The potential applications of the dimension- and dispersion-sensitive EIT responses are discussed, and the sensitivity limits of some waveguide-based sensors, including electric absorption modulator, optical switch, wavelength sensor, and sensitive magnetometer, are analyzed.

DOI: 10.1103/PhysRevA.74.063831 PACS number(s): 42.50.Gy, 78.20.Ci, 42.81.Qb

I. INTRODUCTION

During the past decade, many theoretical and experimental investigations have shown that the control of phase coherence in multilevel atomic systems can exhibit many striking quantum optical phenomena in the wave propagation of nearly resonant light [1]. One of the most interesting phenomena is electromagnetically induced transparency (EIT), which originates from quantum coherence and destructive quantum interference [1]. Some unusual physical effects associated with EIT observed in recent experiments included the ultraslow light pulse propagation, superluminal light propagation, coherent storage of information, photon switching, and atomic ground state cooling [1–4]. As the refractive index of an EIT medium can be controlled by some physical parameters (e.g., intensity of the coupling field and the frequency detuning of the probe light), some remarkable applications such as electromagnetically induced focusing (and hence EIT lens) [5], electromagnetically induced grating [6] and isotope discrimination [7] have been proposed. Since the probe light in EIT system can be coherently manipulated by the external field (control light), the EIT system may play a key role in the light switching technique (photon switching) and coherent information storage [8]. More recently, the resonant optical interaction with molecules confined in a hollow-core photonic-band-gap fiber (and hence fiber-based fast or slow light effects) was demonstrated [9]. Since the waveguide (and fiber) can be used to facilitate strong coherent light-matter interactions [9], the optical properties of EIT vapor in the waveguide deserve consideration. Moreover, the geometric shape of the waveguide [filled with some coherent atomic vapor (EIT vapor)] can dramatically modify the guiding eigenmodes, including the quantum vacuum modes (and hence the atomic spontaneous emission rate is influenced) [10]. This means that the waveguide dimension would have an effect on the EIT vapor in the waveguide. In this paper we study the sensitive influence of the fluctuations (perturbations) of external environmental conditions (which lead to the small changes in waveguide dimension) on the transparency and absorption properties of the EIT vapor.

It is well known that the waveguide boundary condition can determine the mode distribution structures of quantum vacuum fluctuation. Thus the vacuum mode structure in the waveguide is drastically modified as compared to that in the free space. Such a quantum vacuum effect has been studied and observed in cavity QED [11], photonic crystal [12] and Casimir effect [13,14]. As the atomic spontaneous emission decay results from the interaction between the atomic excited states and the quantum vacuum modes, the change of the quantum vacuum mode structure would lead to the dramatic modification to the atomic spontaneous decay rates (and hence to the optical properties of the atomic systems). For example, Paspalakis *et al.* considered some properties (e.g., the control of spontaneous emission) of atomic vapor and EIT medium in structured vacuum (photonic bandgap material and Markovian reservoir) [15–17]. In the literature, electromagnetically induced transparency (including the relevant effects and applications) in free vacuum has been studied by many researchers [1–7], but less attention was paid to the optical properties of EIT in a finite space (say, waveguide) with boundary conditions, particularly the small boundary changes (fluctuations) at resonance. Here we will see how the optical properties of the EIT vapor would depend on the boundary conditions and respond to the variations of the boundary dimension. The sensitive optical effects exhibited in such an EIT waveguide have potential applications such as electric absorption (EA) modulator, optical switch and waveguide sensors.

II. EIT VAPOR IN A WAVEGUIDE

First we consider briefly how the geometric shape of a rectangular waveguide [see Fig. 1(a)] influences the atomic spontaneous emission [18–20]. For simplicity, we assume the rectangular waveguide is formed by a perfectly

*Electronic address: jqshen@coer.zju.edu.cn

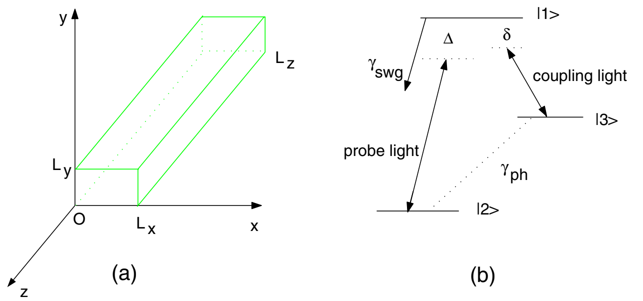

FIG. 1. (Color online) The schematic diagrams of a rectangular waveguide (a) and a three-level Λ-type atomic system interacting with the probe and coupling lights (b). The waveguide is filled with such a three-level atomic vapor.

conducting metal. The coupling strength of a two-level system $\{|1\rangle, |2\rangle\}$ interacting with a probe light field that has transverse mode (m,n) and longitudinal wave vector k in a rectangular waveguide reads [20],

$$g_{mn\sigma} = -\langle 1|e\mathbf{r}|2\rangle \cdot \mathbf{E}_{mn\sigma}(x,y)\sqrt{\frac{2\hbar\omega}{L_x L_y L_z \epsilon_0}}\exp(ikz), \quad (1)$$

where $\mathbf{E}_{mn\sigma}(x,y)$ denotes the transverse modal profile [21], and σ indicates the polarization of the light field. The density of state of the light field can be defined as $\rho_{mn}(\omega)=dN(\omega)/d\omega$ with the total number of states $N(\omega)=2k/(2\pi/L_z)$. By using the dispersion relation $\omega^2=c^2k^2+\omega_{mn}^2$ with $\omega_{mn}=(m^2/L_x^2+n^2/L_y^2)^{1/2}c\pi$, we obtain the density of state

$$\rho_{mn}(\omega) = \frac{\omega L_z}{2c\pi(\omega^2-\omega_{mn}^2)^{1/2}} \quad (2)$$

of the light field in the rectangular waveguide [10]. According to the formula for the spontaneous emission decay rate $[\gamma=(2\pi/\hbar^2)\Sigma_{\mathbf{k}}|g_{\mathbf{k}}|^2\rho(\omega_{\mathbf{k}})_{\omega_{\mathbf{k}}=\omega_a}]$, one can obtain the following atomic spontaneous decay rate of the $|1\rangle$-$|2\rangle$ transition in the waveguide

$$\gamma_{\rm swg} = \sum_{mn\sigma}\frac{2\omega_a^2 e^2}{\epsilon_0\hbar c(\omega_a^2-\omega_{mn}^2)^{1/2}L_x L_y}|\langle 1|\mathbf{r}|2\rangle \cdot \mathbf{E}_{mn\sigma}(x,y)|^2, \quad (3)$$

where the summation is performed over all the waveguide modes with mode frequencies $\omega_{mn}<\omega_a$ (ω_a is the atomic transition frequency, i.e., ω_{12}). Thus, one sees that both the waveguide mode frequency ω_{mn} and the modal profile $\mathbf{E}_{mn\sigma}(x,y)$ may have influences on the spontaneous emission decay rate in the waveguide. As the guiding mode is a standing wave in the transverse direction, the interaction between atoms and probe light depends on the spatial coordinates, and hence the spontaneous emission decay rate $\gamma_{\rm swg}$ is a function of transverse coordinates (x,y).

Now we assume the rectangular waveguide is filled with a three-level EIT vapor. Consider a three-level Λ-type atomic system with one upper level $|1\rangle$ and two lower levels $|2\rangle$ and $|3\rangle$ [see Fig. 1(b)]. Such a three-level system exists in alkali metal atoms, e.g., ^{87}Rb atom with transition of $(D_1 F=2)\to(F'=1)$ ($|1\rangle$-$|2\rangle$ transition) at 795 nm. The atomic system interacts with two optical fields, i.e., the probe and coupling lights, which couple the level pairs $|1\rangle$-$|2\rangle$ and $|1\rangle$-$|3\rangle$, respectively. The frequency detunings of the probe and coupling lights are Δ and δ, which are defined through $\Delta=\omega_{12}-\omega_p$ and $\delta=\omega_{13}-\omega_c$, where $\{\omega_{12},\omega_{13}\}$ denote the $|1\rangle$-$|2\rangle$, $|1\rangle$-$|3\rangle$ transition frequencies, and $\{\omega_p,\omega_c\}$ stand for the frequencies of the probe and coupling lights, respectively. It should be noted that the atoms are assumed to be nearly stationary (e.g., at a low temperature) and hence any Doppler shift is neglected. We assume that the intensity of the probe light is sufficiently weak and therefore nearly all the atoms remain in the ground state $|2\rangle$. Under these conditions, the atomic electric polarizability β_e for the probe light due to the atomic transition between levels $|1\rangle$ and $|2\rangle$ is

$$\beta_e = \frac{i|\wp_{12}|^2}{\epsilon_0\hbar}\frac{\frac{\gamma_{\rm ph}}{2}+i(\Delta-\delta)}{\mathcal{Z}} \quad (4)$$

with

$$\mathcal{Z} = \left(\frac{\gamma_{\rm swg}}{2}+i\Delta\right)\left(\frac{\gamma_{\rm ph}}{2}+i(\Delta-\delta)\right)+\frac{\Omega_c^*\Omega_c}{4}, \quad (5)$$

where $\wp_{12}$, $\gamma_{\rm ph}$, and Ω_c denote the transition dipole matrix element, collisional dephasing rate (nonradiative decay rate) of level $|3\rangle$, and Rabi frequency of the coupling light, respectively. The relative electric permittivity and the relative refractive index of the EIT vapor medium are given by $\epsilon_r=1+N_a\beta_e$ and $n_r=\sqrt{\epsilon_r}$, respectively, where N_a denotes the atomic concentration of the EIT vapor.

In the following sections, we show that the EIT atomic vapor would exhibit the dispersion-sensitive and dimension-sensitive optical responses if the vapor is confined inside a small rectangular waveguide with dimensions of the order of or smaller than the wavelength of the probe field. Such effects can be applicable to designing sensitive devices (i.e., waveguide-based sensors) that can perform precise measurements.

III. DISPERSION-SENSITIVE EFFECTS IN THE WAVEGUIDE

It can be found that the atomic polarizability (and hence the electric permittivity and absorption coefficient) in the waveguide is very sensitive to some parameters such as the waveguide mode frequency ω_{mn} and the probe detuning frequency Δ. This can be interpreted as follows: if the waveguide mode frequency ω_{mn} deviates greatly from the atomic transition frequency ω_a, the atomic polarizability will be reduced to the form $\beta_e=4i|\wp_{12}|^2[\gamma_{\rm ph}/2+i(\Delta-\delta)]/(\epsilon_0\hbar\Omega_c^*\Omega_c)$. The two dimensionless parameters $N_a|\wp_{12}|^2/(\epsilon_0\hbar\Omega_c)\simeq 0.1$ and $|N_a\beta_e|\simeq 10^{-5}$ near resonance, provided that the typical parameters in expression (4) are chosen as $\gamma_{\rm ph}=3.0\times 10^4\ {\rm s}^{-1}$ [2,22], $\Omega_e=1.0\times 10^8\ {\rm s}^{-1}$, and $N_a=2.0\times 10^{19}\ {\rm m}^{-3}$. Typical electric dipole matrix element for alkali metal atoms such as Rb and Ce is $\wp_{12}=3.0\times 10^{-29}$ C m [23,24]. It can be easily seen that the imaginary part of the electric permittivity

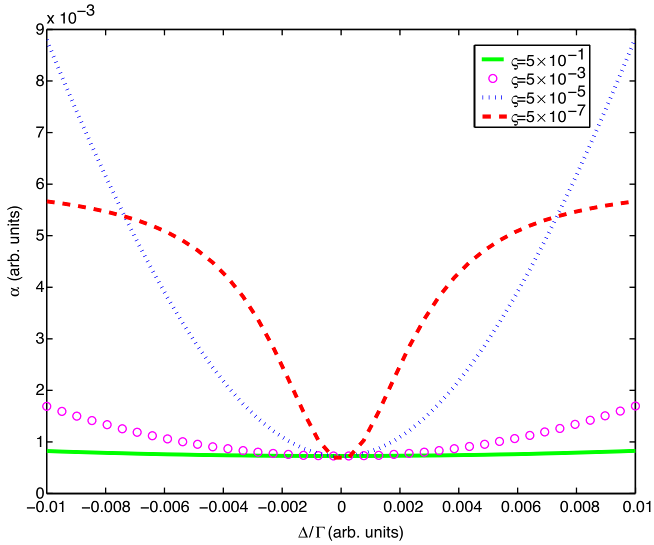

FIG. 2. (Color online). The absorption coefficient (α) of the waveguide as the frequency detuning (normalized with frequency $\Gamma=10^8$ s^{-1}) of the probe field varies. The dispersive behavior of α is sensitive to the small relative frequency deviation ς of the waveguide mode frequency from the atomic transition frequency. The curves correspond to the relative frequency deviations $\varsigma=5\times10^{-1}$, 5×10^{-3}, 5×10^{-5}, 5×10^{-7}, respectively. The case $\varsigma=5\times10^{-7}$ is extremely close to the resonance, while the case $\varsigma=5\times10^{-1}$ is far from the resonance (the waveguide dimension has small effect on the EIT vapor and, in some sense, the optical property of EIT is similar to that in free vacuum).

is negligibly small, and the electromagnetically induced transparency of the probe light in the waveguide will take place in the presence of the strong coupling light (which may lead to a destructive quantum interference as well as quantum coherence effect in the multilevel atomic transition process). However, once the maximum mode frequency ω_{mn} approaches the atomic transition frequency ω_a, the spontaneous emission rate $\gamma_{\rm swg}$ of level $|1\rangle$ in the present waveguide becomes very large, and the atomic polarizability of the three-level system is reduced to that of a two-level one, i.e., $\beta_e\to(i|\wp_{12}|^2/\epsilon_0\hbar)(\gamma_{\rm swg}/2+i\Delta)^{-1}$. This means that there is a serious resonant absorption for the probe light in the waveguide. Thus the optical property of EIT waveguide is very sensitive to the relative frequency deviation, ς, of the mode frequency ω_{mn} from the atomic transition frequency ω_a. Here, the relative frequency deviation is defined by $\varsigma=(\omega_a-\omega_{mn})/\omega_a$. The absorption coefficient α (defined as $2\pi\,\mathrm{Im}\{n_r\}/\mathrm{Re}\{n_r\}$, i.e., the loss in the medium per wavelength) in the waveguide is shown in Fig. 2 as a function of the frequency detuning of the probe light for several different values of relative frequency deviations ς. Here, for convenience, the coupling beam is in resonance with the $|1\rangle$-$|3\rangle$ transition. From this figure one sees that the absorption increases as the frequency detuning of the probe light increases. The absorption near the probe resonant frequency is more sensitive to the probe frequency detuning when $\gamma_{\rm swg}$ has a larger value [i.e., when the maximum mode frequency ω_{mn} (cutoff frequency) is closer to the atomic transition frequency ω_a and hence the frequency deviation ς is very small]. This property can be used to develop, e.g., a highly sensitive wavelength sensor (monitoring a tiny shift in the wavelength of the probe light by simply measuring the variations of the transmitted power of the probe light).

As shown above, the relative frequency deviation ς, which has much influence on the optical property of EIT waveguide, depends on the maximum waveguide mode frequency (cutoff frequency). The mode frequencies are determined by the waveguide boundary condition. This implies that the dispersive behavior of the EIT vapor in the waveguide is in fact very sensitive to the small waveguide dimension changes. In the section that follows, we will consider the dimension-sensitive EIT responses.

IV. SENSITIVE OPTICAL RESPONSES TO THE VARIATIONS OF THE WAVEGUIDE DIMENSIONS

As a very small variation in the waveguide dimensions L_x,L_y will give rise to a corresponding change in the waveguide cutoff frequency (and hence a very large enhancement of the spontaneous emission), the optical properties (transparency and absorption) will be dramatically influenced by the fluctuation (perturbation) in the external environmental conditions (such as the temperature change and pressure on the waveguide boundary surfaces) which will cause some changes in waveguide dimensions. If the environmental temperature change or the surface pressure leads to very small changes $\Delta L_x,\Delta L_y$ in boundary dimensions L_x,L_y, the relative variation in the transverse mode frequency of the waveguide reads

$$\frac{\Delta\omega_{mn}}{\omega_{mn}}=\frac{\dfrac{m^2}{L_x^2}\left(\dfrac{\Delta m}{m}-\dfrac{\Delta L_x}{L_x}\right)+\dfrac{n^2}{L_y^2}\left(\dfrac{\Delta n}{n}-\dfrac{\Delta L_y}{L_y}\right)}{\dfrac{m^2}{L_x^2}+\dfrac{n^2}{L_y^2}}. \tag{6}$$

Here, ω_{mn} and ω'_{mn} $(\equiv\omega_{mn}+\Delta\omega_{mn})$ correspond to the waveguide dimensions $\{L_x,L_y\}$ and $\{L_x+\Delta L_x,L_y+\Delta L_y\}$, respectively. According to expression (3), $\gamma_{\rm swg}$ can be rewritten into a sum of two parts: $\gamma_{\rm swg}=\gamma_0+\gamma_{\rm cut}$, where γ_0 corresponds to all the contributions of the waveguide modes whose mode frequencies are less than the waveguide cutoff frequency $\omega_{mn}^{\rm cut}$, and $\gamma_{\rm cut}$ is the contribution of the cutoff mode. Here the dependence of γ_0 on the variations of the waveguide dimension is negligibly small, while $\gamma_{\rm cut}$ depends strongly on the variations of the waveguide dimension (i.e., $\gamma_{\rm cut}$ is very sensitive to the small dimension change of the waveguide). This can be interpreted as follows: the explicit expression for $\gamma_{\rm cut}$ is

$$\gamma_{\rm cut}=\sum_\sigma\frac{2\omega_a^2e^2}{\epsilon_0\hbar c(\omega_a^2-\omega_{MN}'^2)^{1/2}(L_x+\Delta L_x)(L_y+\Delta L_y)}\times|\langle1|\mathbf{r}|2\rangle\cdot\mathbf{E}_{MN\sigma}(x,y)|^2, \tag{7}$$

where the maximum indices m,n of the cutoff frequency $\omega_{mn}^{\rm cut}$ are assumed to be M,N, respectively. According to expression (6), ω'_{MN} can be rewritten as $\omega_{MN}(1+\eta/2)$ with η being a small variation in waveguide dimensions (see below). Thus the difference between ω_a^2 and $\omega_{MN}'^2$ is

$$\omega_a^2 - \omega_{MN}'^2 = \omega_a^2 - \omega_{MN}^2 - \eta\omega_{MN}^2 + O(\eta^2). \tag{8}$$

Define a small parameter

$$\zeta = \frac{\omega_a^2 - \omega_{MN}^2}{\omega_a^2}, \tag{9}$$

and expression (8) can be rewritten as

$$\omega_a^2 - \omega_{MN}'^2 = \omega_a^2\left(\zeta - \eta\frac{\omega_{MN}^2}{\omega_a^2}\right) \simeq \omega_a^2(\zeta - \eta). \tag{10}$$

According to expressions (3) and (7), the atomic spontaneous decay rate in the waveguide can be rewritten in the form

$$\gamma_{\mathrm{swg}} = \gamma_0 + \frac{\mathcal{A}\omega_a}{(\zeta - \eta)^{1/2}}, \tag{11}$$

where the dimensionless coefficient $\mathcal{A}$ is defined through

$$\mathcal{A} = \sum_\sigma \frac{2e^2}{\epsilon_0\hbar c(L_x + \Delta L_x)(L_y + \Delta L_y)}|\langle 1|\mathbf{r}|2\rangle \cdot \mathbf{E}_{MN\sigma}(x,y)|^2. \tag{12}$$

For a typical optical waveguide filled with alkali atoms, the dimensionless $\mathcal{A}\simeq 1.0\times 10^{-8}$. Here, the waveguide dimensions are taken to be μm, and the typical value of γ_0 (spontaneous decay rate due to waveguide quantum-vacuum modes far off resonance) can be chosen as 1.0×10^7 s^{-1}.

For convenience, the rectangular waveguide is assumed to have a square cross section, and so the allowed maximum positive integers $m=n$. For simplicity, we consider only the influence of the dimension change of L_x, and assume the boundary dimension varies adiabatically (i.e., the transition between waveguide modes cannot be excited by the variation of the boundary dimension L_x). Thus $\Delta m=\Delta n=0$, and then $\Delta\omega_{MN}/\omega_{MN}=\eta/2$ with the relative dimension change $\eta=-\Delta L_x/L_x$. As the dimension variation η increases (i.e., L_x decreases), the cutoff frequency $\omega_{mn}^{\mathrm{cut}}$ increases and approaches the atomic transition frequency ω_a, and consequently leads to a very large γ_{cut}. Thus a strong absorption will be caused by such a large spontaneous emission enhancement. In the present paper, as an illustrative example, we choose the small parameter in expression (9) $\zeta=0.01$. This absorption trend (relative dimension change $\eta<0.01$) is shown in Fig. 3. However, once the relative dimension change η exceeds 0.01 and hence the cutoff frequency $\omega_{mn}^{\mathrm{cut}}$ is just beyond the atomic transition frequency ω_a, the curve of the absorption coefficient will drop immediately (see Fig. 3), i.e., a very small dimension change of the waveguide may lead to a very large influence on the probe light propagation inside the waveguide. This can be interpreted as follows: since now the cutoff frequency $\omega_{mn}^{\mathrm{cut}}>\omega_a$, the cutoff waveguide mode no longer makes contribution to the atomic spontaneous emission and should be ruled out in formula (3). [Note that the summation in formula (3) is performed only over all the waveguide modes with mode frequencies $\omega_{mn}<\omega_a$.] Thus the only retained term in the spontaneous emission decay rate is γ_0 that is not sensitive to the small dimension change of waveguide. Moreover, the frequency separation between modes in the waveguide is relatively large (i.e., $\omega_{MN}\gg\eta\omega_{MN}$), the small change in η will not result in the variation of the maximum mode frequency ω_{MN} (i.e., ω_{MN} cannot easily be replaced by $\omega_{M+1,N}$ or $\omega_{M,N+1}$). This means that the absorption coefficient no longer depends on the waveguide dimension change once the cutoff frequency $\omega_{mn}^{\mathrm{cut}}$ goes beyond ω_a (see Fig. 3).

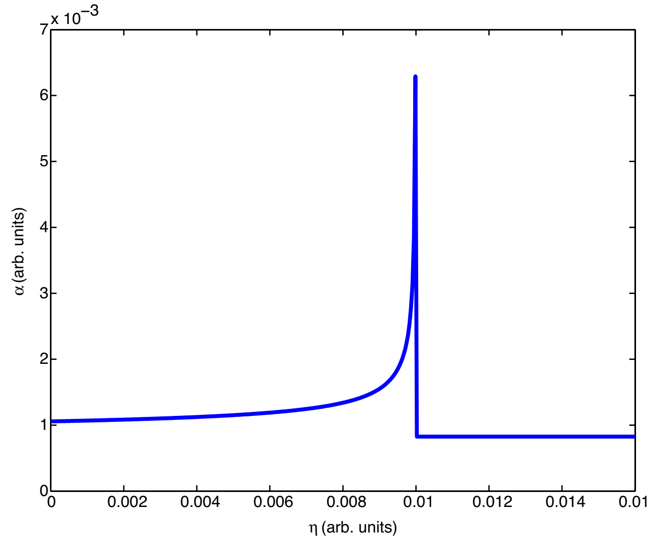

FIG. 3. (Color online) The absorption coefficient (α) as a function of the relative variation (η) of the waveguide dimension. The absorption of the EIT vapor increases as the relative dimension change increases. At $\eta=0.01$ where the waveguide cutoff frequency $\omega_{mn}^{\mathrm{cut}}=\omega_a$, a dramatic absorption enhancement occurs. Once $\eta>0.01$, where $\omega_{mn}^{\mathrm{cut}}>\omega_a$, the contribution of the present cutoff mode is ruled out, and the absorption of the EIT waveguide is no longer sensitive to the waveguide dimension change.

As shown in expression (7), the indices M,N of the cutoff frequency ω_{MN}' for a given waveguide is determined by the probe transition frequency ω_a. This means that the controllable manipulation of optical properties of EIT vapor can be realized by a dc magnetic field that can lead to the level shifts via Zeeman effect (thus the optical response of EIT waveguide is a function of the applied or ambient magnetic field). Such an effect can be utilized to design some sensing techniques such as magnetometer and magnetic field sensors. Besides the sensing applications, the property (dimension-sensitive responses) of the present EIT waveguide could also be used to develop an electric absorption (EA) modulator: specifically, the electric signal voltage could cause a displacement of the waveguide wall through, e.g., some piezo ceramics. In the section that follows, we discuss the working principles and sensitivity limits of some sensors, which take advantage of the optical responses of the EIT waveguide.

V. DISCUSSIONS: THE SENSITIVITY OF WAVEGUIDE SENSORS

As pointed out in the preceding sections, waveguide sensors can exhibit the sensitive optical properties responding to the small changes of external environmental conditions. Here, we will discuss this problem in more detail through analyzing two parameters $d\gamma_{\mathrm{swg}}/d\eta$, $d\alpha/d\Delta$, and see how sensitive the sensors (based on the effects of the confined EIT atomic vapor) would react to the environmental condition changes (including the waveguide dimension changes, probe wavelength shift and external magnetic field changes).

(1) Electric absorption (EA) modulator and optical switch. In the literature, various kinds of EA modulators have been designed by making use of technologies of photonics [25,26]. Here we suggest an alternative way to design a highly sensitive EA modulator using the sensitive optical responses of the confined EIT medium. According to expression (11), the change rate of the spontaneous decay γ_{swg} with respect to the relative variation (η) of the waveguide dimension is

$$\frac{d\gamma_{\text{swg}}}{d\eta} = \frac{1}{2}\frac{\mathcal{A}\omega_a}{(\zeta - \eta)^{3/2}}. \tag{13}$$

If the relative dimension change η deviates quite far from ζ, the spontaneous decay rate will not change much as η increases. However, $d\gamma_{\text{swg}}/d\eta$ would be divergent when the relative dimension change η approaches the resonance ($\eta \to \zeta$), and then a sudden jump of γ_{swg} (and hence the absorption coefficient α) will occur once $\eta \geq \zeta$. The effect of sudden jump in γ_{swg} at resonance can be utilized to realize the EA modulator, where the displacement of the waveguide wall can be caused by the external electric signal voltage. In other words, the electric signal voltage can be used to controllably manipulate the probe propagation in the waveguide.

On the other hand, such a modulator can also be used to measure the electric signal voltage. As the atomic transition frequency ω_a can be shifted by a dc magnetic field (i.e., $\omega_a' = \omega_a + \Delta\omega_a$), one can adjust the added magnetic field strength (proportional to the shifted atomic transition frequency $\Delta\omega_a$) to tune the numerical factor $d\gamma_{\text{swg}}/d\eta$ into resonance, i.e., $\zeta \to \eta$ and the spontaneous decay rate can also experience a sudden jump. Thus, one can obtain a relation between the external electric signal voltage (proportional to η) and the external dc magnetic field (proportional to the transition frequency shift $\Delta\omega_a$),

$$\Delta\omega_a = \frac{\omega_{MN}}{\sqrt{1-\eta}} - \omega_a, \tag{14}$$

when the curve of the spontaneous decay rate exhibits a divergence. This means that the electric signal voltage can be determined by using Eq. (14) when the external dc magnetic field is chosen to make the optical response (spontaneous emission decay) become sharp, as shown in Fig. 3.

Obviously, since both the external magnetic field and the electric signal voltage can control the transmittance of the probe propagation in the waveguide, the above effect has a potential application, e.g., optical switch whose efficiency may be higher than the conventional electric switch, since the atomic relaxation time is only 10 ns. With the explosive data growth in information technology (e.g., optical communications), the network is required of new techniques and gadgets suggested to make networks faster and more reliable. One of the key components is the optical switch. Recently, the technology of so-called all-optical switch on silicon (where physicists can control one light with another light on chip) has been suggested and increasingly developed [27]. We hope the present optical switch based on EIT waveguide would be promising in this field and other related areas such as light-switching photonic circuits (and integrated optical circuits).

(2) Wavelength sensor. The waveguide-based wavelength sensor can be used to measure the probe wavelength. Such a device can be applied to some areas such as color sorting and matching, which need precise measurement of light wavelengths. The sensitivity limit can be analyzed through the following expression:

$$\frac{d\alpha}{d\lambda} = \frac{\omega^2}{2\pi c}\frac{d\alpha}{d\Delta}, \tag{15}$$

where λ denotes the probe wavelength in vacuum. For the EIT vapor in free vacuum, the dispersion $d\alpha/d\Delta$ is not as much as that of the confined EIT vapor in the waveguide (see Fig. 2). The curve $\varsigma = 5\times10^{-7}$ in Fig. 2 is extremely close to the resonance (i.e., the waveguide mode frequency approaches the atomic transition frequency), while the curve $\varsigma = 5\times10^{-1}$ is far from the resonance (and then the waveguide dimension has small effect on the EIT vapor and, in some sense, the optical property of EIT corresponding to the case $\varsigma = 5\times10^{-1}$ is similar to that in free vacuum). It follows that the absorption coefficient α in the case $\varsigma = 5\times10^{-1}$ can be said to be independent of the probe frequency detuning Δ in the narrow band near $\Delta = 0$. However, the strong dispersion (large $d\alpha/d\Delta$) near $\Delta = 0$ can be realized in the waveguide when the relative frequency deviations ς (between the waveguide mode frequency and the atomic transition frequency) are taken to be $\varsigma = 5\times10^{-5}$, 5×10^{-7}. This means that the wavelength sensor in confining space is much more sensitive than that in free vacuum. The sensitivity limit can be evaluated as follows: in Fig. 2, the dispersion in α corresponding to $\varsigma = 5\times10^{-5}$, 5×10^{-7} (the cases of confined EIT vapor) is 10–100 times that of α corresponding to $\varsigma = 5\times10^{-1}$, 5×10^{-3} (the cases close to the behavior of EIT vapor in free vacuum). Thus, we can conclude that the sensitivity limit of the waveguide-based wavelength sensor may increase by one or two orders of magnitude compared with some of the conventional wavelength sensors. Recently, the technology of integrated-optical wavelength sensor has been proposed to detect the wavelength shifts of light sources [28]. We believe that the mechanism presented here can be applied to the area of integrated optics and realize the very highly-precise wavelength-sensitive sensors.

(3) Sensitive magnetometer. In the literature, Fleischhauer *et al.* suggested the working mechanism of so-called optical magnetometer that can be used to detect magnetic fields with high sensitivity because of the large dispersion caused by the atomic phase coherence [29]. As pointed out in Sec. III, the EIT exhibits the dispersion-sensitivity effect in the waveguide. The sensitivity limit of our waveguide-based magnetometer may increase by several orders of magnitude compared with that of the magnetometer presented in Ref. [29]. Here, we discuss the high sensitivity limit of the magnetometer based on EIT waveguide. As is known, the detected magnetic field can lead to the level shift $\Delta\omega_a = (g\mu_B/\hbar)B$,

where g and μ_B denote the gyromagnetic factor and the Bohr magneton, respectively. The change rate of the absorption coefficient α with respect to the detected magnetic induction B is

$$\frac{d\alpha}{dB}=\frac{d\alpha}{d\Delta}\frac{d(\omega_a+\Delta\omega_a-\omega_p)}{dB}=\frac{g\mu_B}{\hbar}\frac{d\alpha}{d\Delta}. \tag{16}$$

As the confined EIT vapor has large numerical factor $d\alpha/d\Delta$ (increasing by one or two orders of magnitude at resonance), the waveguide-based magnetometer would have a much larger sensitivity limit than the regular magnetic field sensors such as the standard optical pumping magnetometer.

VI. CONCLUDING REMARKS

As the quantum-vacuum eigenmode structure in the waveguide can be altered by the waveguide dimension change, the EIT vapor has been suggested in this paper to manipulate the optical properties of the probe light in the waveguide. It has been shown that the optical responses resulting from both electromagnetically induced transparency and large spontaneous emission enhancement are very sensitive to the external environmental fluctuations. This means the optical properties of the confined EIT vapor could be controllably manipulated by the external conditions. On the other hand, the external environmental fluctuations (such as temperature change and acoustic pressure on the waveguide boundary surfaces), which would lead to small changes of waveguide dimensions, could be detected and measured by the EIT-waveguide sensors since the transparency and absorption properties in the EIT waveguide depend strongly on the small dimension changes of waveguide. All these effects can be useful for the development of new technologies in quantum optical and photonic devices (such as sensors and modulators containing the confined EIT vapors). It has been shown that the sensitivity limits of some EIT-based waveguide sensors such as wavelength sensor and sensitive magnetometer can increase by one or two orders of magnitude compared with those already existing devices in free vacuum (without the confinement of waveguide). For instance, if the EIT-waveguide response is applied to the phase-coherent optical devices [29], we might obtain a magnetometer with high accuracy. We hope the waveguide sensors presented here could be realized experimentally in the near future.

ACKNOWLEDGMENTS

This work is supported by the Wenner-Gren Foundations (Sweden) and the National Basic Research Program of China under Grant No. 2004CB719800, and partially financed by the National Natural Science Foundations (NNSF, China) under Contract No. 10604046.

[1] S. E. Harris, Phys. Today **50**(7), 36 (1997).
[2] Y. Q. Li and M. Xiao, Opt. Lett. **20**, 1489 (1995).
[3] J. Q. Shen, Z. C. Ruan, and S. He, Phys. Lett. A **330**, 487 (2004).
[4] H. Schmidt and A. Imamoğlu, Opt. Lett. **21**, 1936 (1996).
[5] R. R. Moseley, S. Shepherd, D. J. Fulton, B. D. Sinclair, and M. H. Dunn, Phys. Rev. Lett. **74**, 670 (1995).
[6] H. Y. Ling, Y. Q. Li, and M. Xiao, Phys. Rev. A **57**, 1338 (1998).
[7] A. Kasapi, Phys. Rev. Lett. **77**, 1035 (1996).
[8] P. Arve, P. Jänes, and L. Thylén, Phys. Rev. A **69**, 063809 (2004).
[9] S. Ghosh, J. E. Sharping, D. G. Ouzounov, and A. L. Gaeta, Phys. Rev. Lett. **94**, 093902 (2005).
[10] D. Kleppner, Phys. Rev. Lett. **47**, 233 (1981).
[11] R. G. Hulet, E. S. Hilfer, and D. Kleppner, Phys. Rev. Lett. **55**, 2137 (1985).
[12] S. John, Phys. Rev. Lett. **58**, 2486 (1987).
[13] H. B. G. Casimir, Proc. K. Ned. Akad. Wet. **51**, 793 (1948).
[14] S. K. Lamoreaux, Phys. Rev. Lett. **78**, 5 (1997).
[15] E. Paspalakis and P. L. Knight, Phys. Rev. Lett. **81**, 293 (1998).
[16] D. G. Angelakis, E. Paspalakis, and P. L. Knight, Phys. Rev. A **64**, 013801 (2001).
[17] E. Paspalakis, N. J. Kylstra, and P. L. Knight, Phys. Rev. A **60**, R33 (1999); E. Paspalakis, D. G. Angelakis, and P. L. Knight, Opt. Commun. **172**, 229 (1999).
[18] D. P. Obrien, P. Meystre, and H. Walther, Adv. At. Mol. Phys. **21**, 1 (1985).
[19] W. S. Dai and M. Xie, Eur. Phys. J. D **19**, 125 (2000).
[20] C. P. Sun, Y. D. Wang, Y. Li, and F. Zhang, "Fundamental concepts and methods in microcavity QED," in *New Progress in Quantum Mechanism*, edited by J. Y. Zeng, G. L. Long, and S. Y. Pei (Tsinghua University Press, Peking, China, 2003), Vol. 3, Chap. 4.
[21] J. D. Jackson, *Classical Electrodynamics*, 3rd ed. (Wiley, New York, 2001), Chap. 8.
[22] M. Yan, E. G. Rickey, and Y. Zhu, Phys. Rev. A **64**, 041801(R) (2001).
[23] T. Hong, Phys. Rev. Lett. **90**, 183901 (2003).
[24] A. Imamoğlu, H. Schmidt, G. Woods, and M. Deutsch, Phys. Rev. Lett. **79**, 1467 (1997).
[25] K. Nishimura, R. Inohara, M. Usami, and S. Akiba, IEICE Trans. Electron. **88**, 319 (2005), and references therein.
[26] J. M. L. Figueiredo, C. R. Stanley, A. R. Boyd, C. N. Ironside, S. G. McMeekin, and A. M. P. Leite, e-print physics/0503140.
[27] S. John and M. Florescu, J. Opt. A, Pure Appl. Opt. **3**, S103 (2001).
[28] U. Grusemann, B. Zeitner, M. Rottschalk, J. P. Ruske, A. Tunnermann, and A. Rasch, Appl. Opt. **41**, 6211 (2002).
[29] M. Fleischhauer and M. O. Scully, Phys. Rev. A **49**, 1973 (1994).