Quantum Surface plasmon resonance system based on electromagnetically -induced transparency

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Abstract

A scheme for a new kind of surface plasmon resonance system (SPR) is proposed. The system is composed of three layers: a prism, a thin metal film, and a hybrid dielectric consisting of EIT atoms and a background substance. It is found that due to the inherently quantum feature of EIT, the EIT-based SPR system exhibits some interesting quantum properties, which are absent in ordinary SPR systems and may be used for novel sensors which can detect very small variations of quantum properties of matters such as small shifts of atomic levels caused by external fields and have sub-wavelength spatial resolution.

1. Introduction

Electromagnetically induced transparency (EIT) is a fascinating effect in which an otherwise opaque medium becomes transparent to a resonant (probe) field by use of another (coupling) field [1]. The destructive quantum interference between two atomic transition pathways leads to null absorption and large dispersion within the induced transparency window. The phenomenon has attracted great attention on account of its potential applications in the coherent control of the optical properties of atomic media and solid systems, e.g. photonic crystals [2], or quantum metamaterials [3]. Recent theoretical investigation has also shown that EIT can be used for coherent control of the group velocity [4] of the polaritons at the surface of a negative-refractive- index metamaterial under the condition of near-zero loss of the polaritons. The key point of this investigation is that the near-zero loss can be realized at special frequencies where the double negative indexes occurs(i.e., the real part of the permittivity and the permeability are both negative). However, for a bulk metal, only the permittivity can have a negative real part in the visible spectrum. So a question arises: for surface-plasmon polaritons at a metal surface, will coherent control based on EIT be possible, or will some other coherent phenomena be observed? It will be shown in this paper that coherent control is indeed tolerant of metal loss, and some very interesting phenomena may be observed, even for an EIT material of very low atomic number density. It will be also shown that new phenomena can occur when surface plasmons are excited under EIT conditions. To my knowledge, an SPR system based on EIT has never been investigated before, and this kind of system may to be used for novel sensors for detecting not only the small variations of refractive index as ordinary SPR system[5], but also the quantum properties such as small shifts of energy-levels of matters with sub-wavelength spatial resolution.

2. EIT in an atomic medium

The EIT medium can be an atomic gas or doped solid medium composed of three-level atoms of Λ configuration. For a single atom, the wavefunction of the electronic state can be written as $|\psi(t)\rangle = c_0(t)|0\rangle + c_1(t)|1\rangle + c_2(t)|2\rangle$, where c_0, c_1, and c_2 are the probability amplitude of the ground state, the excited state, and the second ground state of the atom, respectively.

According to the Schrödinger equation in the interaction picture, the motion of the probability amplitudes can be obtained as follows (with the method similar to Ref. [1])

$$\begin{aligned} i\frac{dc_0}{dt} &= \frac{\Omega_p(x,y,z)}{2}c_1 \\ i\frac{dc_1}{dt} &= -(\delta_p + i\frac{\gamma}{2})c_1 + \frac{\Omega_p(x,y,z)}{2}c_0 + \frac{\Omega_c(x,y,z)}{2}c_2 \\ i\frac{dc_2}{dt} &= -(\delta_p - \delta_c + i\frac{\gamma'}{2})c_2 + \frac{\Omega_c(x,y,z)}{2}c_1 \end{aligned} \quad . \quad (1)$$

Here δ_p is the probe detuning defined by $\delta_p = \omega_p - \omega_{10}$, and δ_c is the coupling detuning defined by $\delta_c = \omega_c - \omega_{12}$, where ω_p and ω_c are the angular frequencies of the probe and coupling fields, respectively, ω_{10} and ω_{12} are the atomic transition angular frequencies of $|1> - |0>$ and $|1> - |2>$ transitions, respectively, Ω_p and Ω_c are the Rabi-frequencies defined by $\Omega_p(x,y,z) = \frac{\overrightarrow{\mu}_{10}\cdot\mathbf{E}_p(x,y,z)}{\hbar}$ and $\Omega_c(x,y,z) = \frac{\overrightarrow{\mu}_{21}\cdot\mathbf{E}_c(x,y,z)}{\hbar}$, respectively, $\mathbf{E}_p(x,y,z)$ and $\mathbf{E}_c(x,y,z)$ are the electric field amplitudes of the probe and the coupling fields, respectively, and, $\overrightarrow{\mu}_{10}$ and $\overrightarrow{\mu}_{21}$ are the transition electronic dipole moments of $|1> - |0>$ and $|1> - |2>$ transitions, respectively. Also, γ and γ' are the decay rates of states $|1>$ and $|2>$, respectively. The quantum interference between $|0> - |1>$ and $|2> - |1>$ transitions can strongly modify the optical response of the system. All the laser fields in this paper are assumed to be monochromatic. In this case, the field amplitudes $\mathbf{E}_p$ and $\mathbf{E}_c$ are time independent. However, it should be noted that, in general cases $\mathbf{E}_p$ or $\mathbf{E}_c$ can be position dependent. For the sake of simplicity, we assume the EIT medium is composed of cold atoms where the Doppler effect can be neglected, and only consider the weak probe field case where

$\Omega_p << \gamma, \Omega_c$. According to Ref. [1], the susceptibility χ can be given by

$$\chi(x,y,z) = -\frac{|\overrightarrow{\mu}_{10}|^2 N}{\hbar\varepsilon_0}\frac{c_0^* c_1}{\Omega_p(x,y,z)}. \quad (2)$$

We consider the transitions of the sodium D2 line. According to Ref. [6], $|\overrightarrow{\mu}_{10}|$ can be evaluated by $|\overrightarrow{\mu}_{10}| = \sqrt{\frac{1}{3}}3.5247ea_0$ with a_0 being the Bohr radius and ε_0 the permittivity of vacuum, and $\gamma = 61.54$MHz. According to Ref. [7], $N = 3 \times 10^{18}/m^3$.

We assume that the atom is initially in the ground state, and probe field is assumed to be very weak so that $c_0(t) \approx 1$ is satisfied at all times. The steady-state solution of Eq.(1) can be easily obtained, and substituting the solution into Eq. (2) , it is easy to obtained that

$$\chi(x,y,z) = -\frac{|\overrightarrow{\mu}_{10}|^2 N}{\hbar\varepsilon_0}\frac{\frac{1}{2}(\delta_p - \delta_c + i\frac{\gamma'}{2})}{-\frac{1}{4}\Omega_c(x,y,z)^2 + (\delta_p + i\frac{\gamma}{2})(\delta_p - \delta_c + i\frac{\gamma'}{2})}. \quad (3)$$

It should be noted that, according to Eq. (3), χ is independent on Ω_p , i.e. the atomic medium is a linear medium for the probe field under the weak-field approximation, and the function $\chi(x,y,z)$ depends on the function $\Omega_c(x,y,z)$.

We assume that the incident coupling beam (in the prism) is a traveling wave with planar wavefront. Under this condition, if we consider the coupling field in the EIT medium, however, we find there are two typical situations:

(1) The coupling field in the EIT medium is a freely-propagating field. In this situation, constant Ω_c lead to a spatially independent susceptibility χ. This result is applicable to all the cases where the probe field in the EIT medium is weak, even to the case where the probe field is a SPP but the coupling field is a freely-propagating field of planar-wave.

(2) The coupling field in the EIT medium a SPP field. In this situation, spatially dependent function $\Omega_c(x,y,z)$ leads to a spatially dependent susceptibility $\chi(x,y,z)$.

The two situations occur for different incident angles (θ_c) and have quite different frequency spectra of reflectivity, which will be discussed later.

3. Surface EIT with a freely-propagating coupling field

In this section we consider the case of freely-propagating coupling field. The scheme of EIT-based SPR is shown in Fig. 1, where the EIT medium can be atomic gases or doped solid medium which are composed of of three-level atoms of Λ configuration.

The coupling field in the dielectric can be a freely propagating field when $\mathrm{Im}(k_{\mathrm{d}x}) = 0$, or an evanescent field when $\mathrm{Im}(k_{\mathrm{d}x}) > 0$, depending on the incident angle θ_c. We can calculate θ_c according to Eqs.(8) and (10). If the

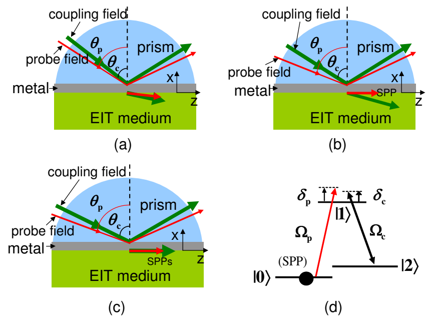

Figure 1: (Color online) Schematic of the system. The system is composed of an atomic EIT medium (green), a metal film(gray), and a cylindrical prism (blue).(a) The case that both of the probe field and the coupling field in the atomic medium are freely propagating fields (no SPR effect). (b) The case that the probe field is a SPP field but the coupling field is a freely propagating field in the atomic medium. (c) The case that both of the probe field and the coupling field are SPP fields. (d) Energy-level diagram of three-level atoms of Λ-configuration.

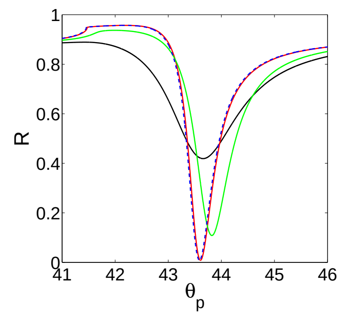

Figure 2: (Color online) Angle-dependence of the probe-field reflectivity (R) for different dielectric layers (Blue dashed: vacuum; Black: two-level atom ($\Omega_c = 0$) with $\delta_p = 0$; Red: EIT atom with $\delta_p = 0$ and $\Omega_c = 1.23\gamma$; Green: EIT atom with $\delta_p = 0.3\gamma$ and $\Omega_c = 1.23\gamma$. The atomic transitions are of sodium D2 line where $\lambda_0 = 589.1$ nm (probe-field wavelength); $\gamma = 61.54$ MHz, $\omega_{20} = 1.8$ GHz. Other parameters: $n_{\mathrm{p}} = 1.51$, $N = 3.3 \times 10^{18}/m^3$, $\varepsilon_{\mathrm{m}} = -13.3 + 0.883i$ [15] (which is approximated a constant within EIT frequency-band (about 100 MHz)), and $q = 50$ nm(thickness of the silver film).

imaginary parts of n_{p} and ε_d can be neglected, we can easily obtain the critical angle with the equation $k_{\mathrm{d}x}^2 = 0$, i.e. $n_{\mathrm{p}} \sin\theta = \sqrt{\varepsilon_{\mathrm{d}}}$, which gives the critical angle θ_{crt}. For $n_{\mathrm{p}} = 1.51$ and $\varepsilon_{\mathrm{d}} = 1$, we obtain $\theta_{crt} = 41.47^o$.

In the case of $\theta_c < \theta_{crt}$, the coupling field in the dielectric is a freely propagating field (shown in Fig. 1(a) and (b)), and Ω_c is spatially independent. With effective-medium theory and taking into account local-field effects for generality, the permittivity of the atomic medium can be given by [8, 9]

$$\varepsilon_d = \varepsilon_b + \frac{\chi}{1-\frac{1}{3}\chi}\frac{\varepsilon_b+2}{3}, \quad (4)$$

where ε_b is the background permittivity and χ is given by Eq.(3). The background is assumed to be an vacuum (ε_b=1) or a very dilute dielectric ($\varepsilon_b \approx 1$). Here N is the density of the atomic number. So ε_d can be easily obtained with above equationsin particular, for dilute vapors ($\frac{1}{3}\chi << 1$), ε_d can be given by $\varepsilon_d \approx \varepsilon_b + \chi$.

It should be noted that, because the coupling field only drives transition $|2> - |1>$ of the atoms and the population in state $|2>$ is near zero at all times, the effect of the atoms on the coupling field can be safely neglected. So we only consider the effect of the atomic medium on the probe field. We now calculate the reflectivity R of the probe beam defined by $R = |r_{\rm pmd}|^2$, where $r_{\rm pmd}$ is the three-layer amplitude reflection coefficient and is given by the Fresnel formula

$$r_{\rm pmd} = \frac{r_{\rm pm} + r_{\rm md}\exp(2ik_{{\rm m}x}q)}{1 + r_{\rm pm}r_{\rm md}\exp(2ik_{{\rm m}x}q)}, \quad (5)$$

where q is the thickness of the metal film, and the two-layer amplitude reflection coefficients $r_{\rm pm}$ and $r_{\rm md}$ at the prism/metal and metal/dielectric interfaces, respectively, are given by

$$r_{\rm pm} = \frac{\varepsilon_{\rm m}k_{px} - \varepsilon_{\rm p}k_{{\rm m}x}}{\varepsilon_{\rm m}k_{px} + \varepsilon_{\rm p}k_{{\rm m}x}} \quad (6)$$

and

$$r_{\rm md} = \frac{\varepsilon_{\rm d}k_{{\rm m}x} - \varepsilon_{\rm m}k_{{\rm d}x}}{\varepsilon_{\rm d}k_{{\rm m}x} + \varepsilon_{\rm m}k_{{\rm d}x}}. \quad (7)$$

Here k_z is parallel wave vector and can be given by

$$k_z = k_0 n_{\rm p}\sin\theta_p, \quad (8)$$

where

$$k_0 = \frac{\omega_p}{c}, \quad (9)$$

and k_{jx} are normal wave vectors and can be given by

$$k_{jx} = \sqrt{k_0^2\varepsilon_j - k_z^2} \quad (10)$$

with $j = {\rm p, m, d}$ denoting the prism, the metal, and the dielectric (EIT medium), respectively. The field enhancement due to surface plasmon is defined by [10] $T = |t_{\rm pmd}|^2$ with $t_{\rm pmd} = \frac{H_y(m/d)}{H_y(p/m)}$, where $H_y(m/d)$ and $H_y(p/m)$ are the magnetic field at metal/dielectric and prism/metal interfaces, respectively, and $t_{\rm pmd}$ can be calculated with the Fresnel formula

$$t_{\rm pmd} = \frac{t_{\rm pm}t_{\rm md}\exp(ik_{{\rm m}x}q))}{1 + r_{\rm pm}r_{\rm md}\exp(2ik_{{\rm m}x}q)}, \quad (11)$$

where $t_{ij} = 1 + r_{ij}$ being derived from the boundary conditions, and $i, j = {\rm p, m}$ or $i, j = {\rm m, d}$. Similarly, we can also calculate the field enhancement of the electric field T_e, which is defined by $T_e = \frac{|\mathbf{E}(m/d)|^2}{|\mathbf{E}(p/m)|^2}$, where $\mathbf{E}(m/d)$ and $\mathbf{E}(p/m)$ are the electric field at metal/dielectric and prism/metal interfaces, respectively. For TM polarization, according to Ref. [10], the relation between T_e and T is given by $T_e = \frac{\varepsilon_{\rm p}}{\varepsilon_{\rm d}}T$.

With Eqs.(3) and (4), we can calculate the permittivity of the atomic medium, and, in combination with Eqs. (5), (6), (7),(8), (9), and (10), we can calculate the reflectivity (R) of the probe-field laser beam. It is found that the probe-field reflectivity is strongly influenced by the coupling laser via the quantum interference effect in the EIT medium.

4. Surface EIT with a SPP coupling field

In this section we consider the case of SPP coupling field. The SPP coupling field is resonantly excited by the incident coupling beam when $\theta_c \approx \theta_{res}$ ($\theta_{res} > \theta_{crt}$), and can be numerically determined by the angle of minimum reflectivity of the coupling beam. For an evanescent-wave coupling field ($\theta_c > \theta_{crt}$), the Rabi-frequency (Ω_c) can be written as $\Omega_c(x) = \Omega_{c0}e^{-ik_{{\rm v}x}^{(c)}x}$, where $x < 0$ (i.e. in the atomic medium), and,

$$k_{{\rm v}x}{}^{(\rm c)} = \sqrt{\frac{\omega_c^2}{c^2} - k_z^{(\rm c)}{}^2}, \quad (12)$$

$$k_z^{(\rm c)} = \frac{\omega_c}{c}n_{\rm p}\sin\theta_c. \quad (13)$$

In resonant case when SPP is excited, i.e. $\theta_c \approx \theta_{res}$, we obtain that $k_{vx}{}^{(c)} \approx i\kappa^{(c)}$ with $\kappa^{(c)}$ being a real number which represent the attenuation of the SPP in x-direction. In this case, to calculate the reflection coefficient at metal/dielectric interface ($r_{\rm md}$), we firstly consider the three-layer (metal/vacuum/dielectric) structure and then set the thickness of the vacuum layer ($q_{\rm v}$) to be zero.

The magnetic field $\mathbf{H}$ of the incident field is given by $\mathbf{H} = H_{Iy}\mathbf{e}_y$ with $H_{Iy}(x,z) = A_I e^{-ik_{{\rm v}x}x + ik_z z}$, where A_I is the field amplitude, and $k_{{\rm v}x}$ is the x-component of the wavevector in the vacuum layer being given by

$$k_{{\rm v}x} = \sqrt{\frac{\omega_p^2}{c^2} - k_z^2}, \quad (14)$$

and k_z is given by Eq. (8).

The three-layer (metal/vacuum/dielectric) amplitude reflectivity is given by

$$r_{\rm mvd} = \frac{r_{\rm mv} + r_{\rm vd}\exp(2ik_{\rm vx}q_{\rm v})}{1 + r_{\rm mv}r_{\rm vd}\exp(2ik_{\rm vx}q_{\rm v})}. \quad (15)$$

Set $q_{\rm v} = 0$, we obtain two-layer (metal/dielectric) amplitude reflectivity $r_{\rm md}$:

$$r_{\rm md} = \frac{r_{\rm mv} + r_{\rm vd}}{1 + r_{\rm mv}r_{\rm vd}}, \quad (16)$$

where

$$r_{\rm mv} = \frac{k_{{\rm m}x} - \varepsilon_{\rm m}k_{{\rm v}x}}{k_{{\rm m}x} + \varepsilon_{\rm m}k_{{\rm v}x}}. \quad (17)$$

We now calculate $r_{\rm vd}$. We consider a probe field propagating in vacuum is made incidence on the the dielectric

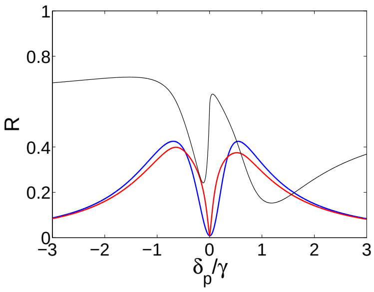

Figure 3: (Color online) Reflectivity of the probe laser beam R versus the probe-detuning δ_p for $\theta_p = 43.61^{\mathrm{o}}$. The blue curve is for freely-propagating coupling field ($\theta_c < \theta_{crt}$) and $\varepsilon_{\mathrm{b}} = 1$; The other (red and black) curves are for SPP coupling field in the case of $\theta_c \approx \theta_p$ (red for $\varepsilon_{\mathrm{b}} = 1$ and black for $\varepsilon_{\mathrm{b}} = 1.005$). Here $\Omega_c = \Omega_{c0} = 1.2A$, other parameters are same as that in Fig. 2

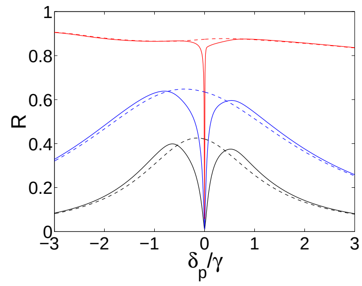

Figure 4: (Color online) Detuning spectra of the reflectivity R for $\theta_p = 43.61^{\mathrm{o}}$ but different atomic densities, where the coupling field is a SPP in the case of $\theta_c \approx \theta_p$. The solid curves are for $\Omega_{c0} = 1.2A$, while the dashed curves are for $\Omega_{c0} = 0$ (Black: $N = 3.3 \times 10^{18}/m^3$; blue: $N = 8 \times 10^{18}/m^3$; red: $N = 8 \times 10^{19}/m^3$.). Other parameters are the same as in Fig. 2.

surface. If $\varepsilon_{\mathrm{d}}(x) \approx 1$, with perturbation theory similar to that in Ref. [11], the reflection field can be written as

$$H_{Ry}(x,z) = A_I e^{ik_z z} k_0^2 \int_{-\infty}^{0} G(x-x')\left[\varepsilon_{\mathrm{d}}(x') - 1\right] e^{-ik_{\mathrm{v}x}x'}\, dx'. \tag{18}$$

The Green function $G(x - x')$ is given by

$$G(x-x') = \frac{i}{2k_{\mathrm{v}x}} e^{ik_{\mathrm{v}x}(x-x')} \tag{19}$$

The amplitude reflectivity r_{vd}, which is defined by $\frac{H_{Ry}(0,z)}{H_{Iy}(0,z)}$, can be obtained by substituting Eq. (19) into (18) as follows

$$r_{\mathrm{vd}} = \frac{k_0^2}{k_{\mathrm{v}x}^2}\left[\varepsilon_{\mathrm{b}} - 1 - \frac{|\overrightarrow{\mu}_{10}|^2 N}{\hbar\varepsilon_0}\frac{1}{\delta_p + i\gamma/2} F(1,b;1+b;1/\beta)\right] \tag{20}$$

where F is the general hypergeometric function[12], and,

$$b = -ik_{\mathrm{v}x}/\mathrm{Im}[k_{\mathrm{v}x}{}^{(c)}], \tag{21}$$

$$\beta = \frac{4(\delta_p + i\gamma/2)(\delta_p - \delta_c + i\gamma'/2)}{\Omega_{c0}^2}. \tag{22}$$

In the typical case when $\omega_p \approx \omega_c$ (e.g. $\omega_p - \omega_c \approx 1.8$ GHz in the EIT experiment of Ref.[7]), if we take $\theta_p = \theta_c$, according to Eqs.(14), (12), (13), and (8), it is easy to see that $k_{\mathrm{v}x} \approx k_{\mathrm{v}x}{}^{(c)} = i\mathrm{Im}[k_{\mathrm{v}x}{}^{(c)}]$, and therefore it is obtained from Eq. (21) that $b \approx 1$. Substituting it into Eq. (20)), we obtain

$$r_{\mathrm{vd}} = \frac{k_0^2}{k_{\mathrm{v}x}{}^2}\left[\varepsilon_{\mathrm{b}} - 1 - \frac{|\overrightarrow{\mu}_{10}|^2 N}{\hbar\varepsilon_0}\frac{\beta}{\delta_p + i\gamma/2}\ln(1-1/\beta)\right], \tag{23}$$

Using Eqs. (15), (16), (17), (23), and (8), we can numerically calculate the reflectivity of the probe beam (R). The incident-angle-dependence of reflectivity is shown in Fig. 2. It obvious that the angle-dependence of reflectivity $R(\theta_p)$ will be strongly modified by the coupling field and the resonance angle (i.e. the dip in the Fig. 2) is very sensitive to the probe detunings (δ_p). When the dielectric is an EIT medium and $\delta_p = 0$, the $R(\theta_p)$ curve is very close to that when there is a vacuum. If the probe field is slightly detuned from resonance, e.g. $\delta = 0.5\gamma$, the resonance angle (i.e. the dip in the $R(\theta_p)$ curve) will be significantly shifted. For the two-level case, however, the minimum of R is much larger than in the EIT case. Similar phenomena can also occur on the field enhancement factors (T and T_e) . This kind of properties may be used for detecting the very small atomic-level shifts induced by external fields. In this sense this SPR system can be regarded as a quantum SPR system.

The probe-detuning dependence is shown in Fig. 3. Because of very steep dispersion of the atomic medium for the probe field, the reflectivity spectrum R is extremely sensitive to the probe detuning δ_p. If both the lasers are monochromatic, then the variations of δ_p and δ_c account for atomic level shifts induced by environmental fields, e.g. by DC magnetic fields via the Zeeman effect. It should be emphasized that a probe-field SPP strongly confined in the metal/EIT medium interface only responds to a DC magnetic field very near the interface. Consequently, it may be possible to apply this EIT-SPR system in novel magnetometers for highly localized measurements.

It is also found from Fig. 3 that the reflectivity spectrum R is sensitive to variation of the substrate permittivity ε_{b}. For a dilute-gas EIT medium, a small increase in ε_{b} can be caused by another background dilute gas mixed with the EIT gas. It is shown that a variation of only 5/1000 of ϵ_{b} can dramatically change the reflectivity spectrum (see Fig. 3, red curve for $\varepsilon_{\mathrm{b}} = 0$, while black curve for $\varepsilon_{\mathrm{b}} = 1.005$). Although ε_{b} depends on ω_p in general, it is frequency independent within the ultra-narrow EIT transparency window. The substrate sensitivity of the spectrum may possibly be used for chemical or biological sensors.

The detuning spectrum of the reflectivity R is also strongly dependent on the atomic number density of the EIT medium , as shown in Fig. 4. In the two-level case there is a peak in the $R(\delta_p)$ spectrum, which becomes broader with the increase of the atomic number density N. In the EIT case, however, a very narrow dip appears at the center of the background peak. It is interesting that as N increases the dip becomes narrower but the background peak becomes broader.

5. Interpretation of the resonant excitation of the probe-field SPP

In order to understand the resonant phenomena we roughly evaluate the propagation constant of the probe field SPP (k_{SPP}). We consider a weak probe field polariton [transverse magnetic (TM) mode] at the interface between a homogeneous dielectric and a metal of semi-infinite medium. From the surface boundary conditions for an SPP wave vector, its magnetic field can be given by [13, 14]

$$H_y = H_{y0} e^{i k_{\mathrm{spp}} z \pm \kappa_{\mathrm{m,d}} x} \tag{24}$$

where '+' is for $x < 0$, while '−' is for $x > 0$, and H_{y0} is field-amplitude. k_{spp} and $\kappa_{\mathrm{m,d}}$ are given by

$$k_{\mathrm{spp}} = k_0 \sqrt{\frac{\varepsilon_{\mathrm{d}} \varepsilon_{\mathrm{m}}}{\varepsilon_{\mathrm{d}} + \varepsilon_{\mathrm{m}}}} \tag{25}$$

and

$$\kappa_{\mathrm{m,d}} = \sqrt{k_{\mathrm{spp}}^2 - k_0^2 \varepsilon_{\mathrm{m,d}}}, \tag{26}$$

where ε_{d} and ε_{m} are the permittivities of the dielectric and the metal, respectively. For the EIT case, ε_{d} will be coherently controlled by the coupling field. Because the EIT 'transparency' range is very narrow (about 100 MHz)), the frequency dependence of ε_{m} can be safely neglected. The probe field wavelength is taken to be about 589.1 nm, where, according to experimental data [15], $\varepsilon_{\mathrm{m}} = -13.3 + 0.883i$, and the imaginary part accounts for metal loss.

It should be emphasized that the amplitude of the electric component of the coupling field $\mathbf{E}_c$ is spatially independent for freely propagating (traveling) fields, but decays exponentially with x for SPP. Only in the former case is ε_{d} spatially independent and Eqs. (25) and (26) are valid. For a coupling-field SPP, $\Omega_c(x) = \Omega_{c0} e^{\mathrm{Re}[\kappa_c] x}$, then ε_{d} will depend on x. If the variation of the refractivity satisfies $\delta n_{\mathrm{d}} << n_{\mathrm{b}} \approx 1$, then the SPP propagation constant k_{spp} can be calculated by perturbation theory [11]:

$$k_{\mathrm{spp}} = k_{\mathrm{spp}}^{(0)} + \delta k_{\mathrm{spp}} \tag{27}$$

where

$$\delta k_{\mathrm{spp}} = \frac{1}{2} \frac{k_0^2}{k_{\mathrm{spp}}^{(0)}} \mathrm{Re}\left[\kappa_p^{(0)}\right] \int_{-\infty}^{0} e^{2\mathrm{Re}\left[\kappa_p^{(0)}\right] x} \left[\varepsilon_{\mathrm{d}}(x) - 1\right] dx. \tag{28}$$

According to Eq. (26) the zeroth-order propagation constant and confinement are $k_{\mathrm{spp}}^{(0)}(\omega_i) = \frac{\omega_i}{c}\sqrt{\frac{\varepsilon_{\mathrm{m}}(\omega_i)}{1+\varepsilon_{\mathrm{m}}(\omega_i)}}$, and $\kappa_i^{(0)} = \frac{\omega_i}{c}\sqrt{\frac{1}{1+\varepsilon_{\mathrm{m}}(\omega_i)} - \varepsilon_b}$, respectively ($i = p, c$ denote 'probe' and 'coupling' ,respectively).

If the difference of the two ground states is very small compared with the laser frequencies, e.g. 1.8GHz in the experiment of Ref.[7], then $\varepsilon_{\mathrm{m}}(\omega_p) \approx \varepsilon_{\mathrm{m}}(\omega_c)$, and then $\kappa_p^{(0)} \approx \kappa_c$, where the superscript 0 denotes 'zeroth order', i.e. the case when the dielectric is vacuum. Thus we obtain

$$\delta k_{\mathrm{spp}} = \frac{1}{2} \frac{k_0^2}{k_{\mathrm{spp}}^{(0)}} \left[\varepsilon_{\mathrm{b}} - 1 + \frac{|\vec{\mu}_{10}|^2 N}{\hbar \varepsilon_0} \frac{\beta}{\delta_p + i\gamma/2} \ln(1 - 1/\beta)\right]. \tag{29}$$

Within the EIT transparency window, $\mathrm{Im}(k_{\mathrm{spp}}) \approx 0$, i.e. the polaritons only suffer low losses. Fig. 5 shows the probe-detuning dependence of the propagation constant, $k_{\mathrm{spp}}(\delta_p)$. The ultra-narrow bandwidth of transparency and the steep dispersion of the bulk EIT-medium leads to a sharp dip in $\mathrm{Im}[k_{\mathrm{spp}}(\delta_p)]$ (blue dashed curve) and a large gradient of the function $\mathrm{Re}[k_{\mathrm{spp}}(\delta_p)]$ (blue solid curve), and therefore lead to a sharp resonant excitation of SPP. Although more accurate calculation for k_{spp} should consider the role of the thickness of the metal film (see eg. Ref. [10]), the rough evaluate here present a simple and qualitative explanation of the sharp dip in the reflectivity spectrum $R(\delta_p)$.

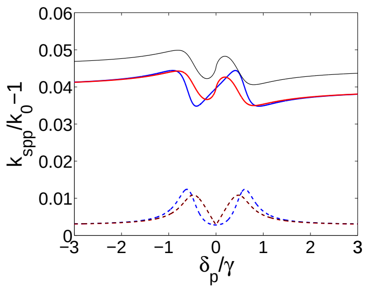

Figure 5: (Color online) Probe-detuning dependence of $k_{\mathrm{spp}}/k_0 - 1$, where k_{spp} is the propagation constant of the probe-field SPP (the solid and dashed curves denote its real and imaginary parts, respectively). Black curves are for SPP coupling field and $\varepsilon_{\mathrm{b}} = 1.005$; Blue curves are for freely-propagating coupling field and $\varepsilon_{\mathrm{b}} = 1$; Red curves are for SPP coupling field and $\varepsilon_{\mathrm{b}} = 1$. The parameters are the same as in Fig. 3.

It is interesting that, comparing the two cases: the coupling field is a SPP and that it is a freely-propagating field, we find in the formal case the gradient of the $\mathrm{Re}[k_{\mathrm{spp}}(\delta_p)]$ curve is more steep(see red solid curve in Fig. 5.), and the dips in $\mathrm{Im}[k_{\mathrm{spp}}(\delta_p)]$ (see red dashed curve in Fig. 5) is pointed, which lead to pointed dip in $R(\delta_p)$ (see the red curve in Fig. 3). The pointed dips arises from the strong confinement of the coupling-field SPP which are absent in ordinary EIT systems, and are signatures of the surface EIT and should be observable experimentally.

6. Discussion

The coupling field will be an evanescent field if $\theta_c > \theta_c^{(crt)}$, but will be a freely propagating field if $\theta_c < \theta_c^{(crt)}$. In practice, the EIT-SPR system may be realized with three different schemes using different arrangements of the coupling field, as follows.

(1) With thin silver films (e.g. $q = 20 - 30$ nm) and a normally incident coupling beam.

(2) With thicker silver films (e.g. 50 nm) and a TM (p-polarized) coupling field with the incidence angle of $\theta_c \approx \theta_c^{(crt)}$. In this case $T_e \approx 0.47$.

(3) With an incidence angle of $\theta_c \approx \theta_{res}$. Similar to (2) but the field enhancement factor T_e is very large($T_e \approx 100$ for 50 nm silver film). Hence the EIT -based coherent control is effective even if the coupling-field at the input end of the system is very weak, which may be used for low-light-level optical switching. .

It should also be noted that although here both the coupling and the probe fields are assumed to be classical, we should consider the possibility of observing nonclassical phenomena arising from the quantum properties of EM fields. The large field-enhancement effect can lead to strong coupling between photon and atom. Further investigation should be made on the quantum state exchange between photon and atom in this SPR system, which may attract broad interest due to its potential applications in quantum information science.

7. Conclusions

In conclusion, a new kind of surface-plasmon-resonance system is proposed which is based on EIT effect of atomic medium. It is found that this system has remarkable quantum properties, i.e. can be extremely sensitive to the small variations of the quantum properties of the detected matters such as their energy-level shifts, and therefore may be used for novel sensors for detecting quantum state of matters, novel magnetometers with subwavelength resolution, and nano-optical devices for quantum information processing.

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