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Lateral shift dependence of spontaneous emission in a planar cavity with perfect conducting cladding

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Abstract. We consider the effect of lateral shift of the "beams" resulting from the atom emissions on spontaneous decay of an excited atom embedded in a planar cavity with perfect conducting cladding. It is found that the spontaneous decay could be enhanced or suppressed owing to the positive and negative lateral shift at the interfaces of the cavity mirror. Compared with the emission between two perfect conducting plates, the surface guided modes could exist and for very thin planar cavity, the density of surface guided modes may be obviously larger than those of the propagating guided modes.

PACS. 42.50.Ct Quantum description of interaction of light and matter; related experiments – 42.25.-p Wave optics

1 Introduction

How to modify and control spontaneous emission has attracted a lot of attention since many interesting phenomena are relevant to spontaneous emission of an excited atomic system. It has been proven that spontaneous decay can be enhanced or suppressed by varying the environment surrounding the given atom so that the atom interacts with a modified set of vacuum modes and there are different densities of modes [1,2] which determine the spontaneous decay rate in different environments. The spontaneous emission properties of atoms in different situations have been extensively investigated theoretically, for example, (a) the principle of reduction of effective mode volume in high index contrast optical microcavities was presented [3], which can be applied to enhance atomic spontaneous emission, (b) an exited atom between two metallic nanospheres which are separated by a very small distance with a few nm [4], (c) emission in the multilayer dielectric planar cavity [5], (d) emission between two conducting plates [6], and (e) spontaneous emission from atoms embedded in a photonic crystal [7]. A different feature that we wish to elucidate here, that seems promising for the purpose of intuitively understanding the spontaneous emission in different environments, is the lateral shift of the "beams" resulting from atom emissions on the spontaneous emission in a planar cavity. Recently, the lateral shift of the reflected beam at an interface between different materials was analyzed both theoretically [8–10] and experimentally [11,12]. It is common knowledge that a totally reflected beam experiences a lateral shift (LS) from its position predicted by the geometric optics because each of its plane-wave components undergoes a different phase change. For the beam reflected from an interface, the LS is usually much less than the beam width. However, large LS could be achieved by utilizing different situations. For example, large positive and negative lateral optical beam shifts have been discovered in the systems with a metal-air interface when the surface plasmon of the metal is resonantly excited [13], a weakly absorbing left-handed slab [14], and a dielectric slab backed by a metal [15]. In reference [15], the LS denotes the displacement of the reflected beam from the path of the geometrical optics at the interface between the vacuum layer and the dielectric layer. The LS of the reflected beam can be negative with the advantage that the reflected beam intensity is almost equal to the incident intensity at any incidence angle. The physics behind the negative LS is the interference between the two reflected waves from two interfaces. So the discovery of large positive and negative lateral optical beam shifts interests us in how the LS of the "beams" resulting from the atom emissions affects the spontaneous emission rate of an exited atom embedded in such a structure proposed by Wang et al. [15]. Here, we will show the different effects between positive and negative LS on the spontaneous emission rate.

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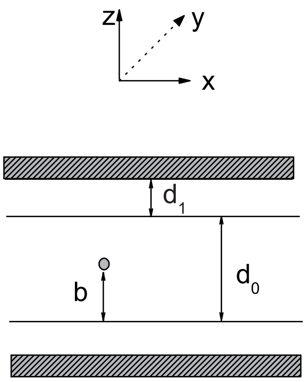

Fig. 1. A planar cavity with perfect conducting cladding and an excited atom embedded in it.

In this paper, we investigate the spontaneous emission from an excited two-level atom embedded in a planar cavity with perfect conducting cladding and find that in this structure, the evanescent guided modes contribute to the decay rate in addition to the propagating guided modes, different from those for the structure that there is no dielectric layers (i.e., the atom is located only between two perfect conducting layers) the evanescent guided modes could not exist. The effects of negative and positive LS of the "beams" resulting from the atom emissions on the spontaneous emission rate are discussed. Firstly, the model is presented. Then the expressions of the spontaneous emission rate from the contribution of the propagating guided modes and the lateral shift are given. The influence of the thickness of the dielectric layer on the decay rate is studied, the physics behind the influence is the effect of LS of the "beams" resulting from the atom emissions at the interfaces of the cavity mirror. Moreover the effect of the thickness of the planar cavity in which the atom is placed on the spontaneous emission rate from the contribution of the surface guided modes is also discussed. Finally, we conclude with a brief summary.

2 Model

We consider an exited two-level atom to be placed in a planar cavity with the permittivity ε_0 (labeled 0 and $\varepsilon_0 = 1$), the upper (lower) cavity mirror formed by a nonmagnetic dielectric layer (labeled 1) and perfect conducting cladding (labeled 2). The permittivity of the nonmagnetic dielectric layer is ε_1 ($\varepsilon_1 > 1$). The direction normal to interfaces of the cavity mirror is named as z-axis as depicted in Figure 1. The spontaneous emission γ is expressed as [16]

$$\gamma = \frac{d^2\omega^2}{\hbar\epsilon_0 c^2}\vec{\epsilon}^* \cdot \mathrm{Im}\overset{\leftrightarrow}{G}(\vec{r}_0, \vec{r}_0; \omega) \cdot \vec{\epsilon}, \tag{1}$$

where ω is the atomic transition frequency, d the strength of atomic dipole moment, $\vec{\epsilon}$ the unit vector of the atomic dipole moment, $\vec{r}_0 = (x_0, y_0, b)$ the atomic position in the planar cavity, $\overset{\leftrightarrow}{G}(\vec{r}_0, \vec{r}_0; \omega)$ represents the electromagnetic Green tensor. For the model under consideration, the Green tensor then satisfies the equation [17]

$$\begin{aligned}\overset{\leftrightarrow}{G}(\vec{r}_0, \vec{r}_0; \omega) = {} & \vec{e}_x\vec{e}_x G_{0xx}(b;\omega) + \vec{e}_y\vec{e}_y G_{0yy}(b;\omega) \\ & + \vec{e}_z\vec{e}_z G_{0zz}(b;\omega),\end{aligned} \tag{2}$$

in which

$$\begin{aligned}G_{0xx}(b;\omega) &= G_{0yy}(b;\omega) \\ &= \frac{i\mu_0}{8\pi k_0^2}\int_0^\infty \frac{dkk}{\beta_0}\left[\frac{\beta_0^2}{D_{p0}}(1 - r_{0-}^p e^{2i\beta_0 b})\right. \\ &\quad \times (1 - r_{0+}^p e^{2i\beta_0(d_0-b)}) + \frac{k_0^2}{D_{s0}}(1 + r_{0-}^s e^{2i\beta_0 b}) \\ &\quad \left.\times (1 + r_{0+}^s e^{2i\beta_0(d_0-b)})\right],\end{aligned} \tag{3}$$

$$\begin{aligned}G_{0zz}(b;\omega) = {} & \frac{i\mu_0}{8\pi k_0^2}\int_0^\infty \frac{dkk}{\beta_0}\frac{2k^2}{D_{p0}}(1 + r_{0-}^p e^{2i\beta_0 b}) \\ & \times (1 + r_{0+}^p e^{2i\beta_0(d_0-b)}),\end{aligned} \tag{4}$$

where $k_0 = \omega/c$, the parameter k is the magnitude of the vector $\vec{k} = (k_x, k_y)$, the conserved component of the wave vector is parallel to interfaces of the cavity mirror, and the β_0 is the magnitude of the z component of the wave vector in the planar cavity, whose definition depends on the value of k [18]. If $k < k_0$, β_0 is expressed as $\beta_0 = \sqrt{k_0^2 - k^2}$, then the corresponding wave in the planar cavity is a propagating one. On the other hand, if $k > k_0$, then $\beta_0 = i\sqrt{k^2 - k_0^2}$ corresponds to an evanescent wave in the planar cavity. The symbol p stands for the electric field of the TM electromagnetic wave, whose polarization is in the plane formed by the two vectors $\vec{k}$ and $\vec{e}_z$, and s stands for the electric field of the TE electromagnetic wave, whose polarization along the $\vec{k} \times \vec{e}_z$ direction. These two kinds of electric fields are hereafter referred to as p- and s-polarized waves or modes, respectively. In addition, the function $D_{q0}(q = p, s)$ are defined as

$$D_{q0} = 1 - r_{0-}^q r_{0+}^q \exp(2i\beta_0 d_0), \tag{5}$$

with $r_{0\pm}^q$ being the reflection coefficient of the upper (lower) cavity mirror. These coefficients obey the usual Fresnel recurrence relation

$$r_{0-}^q = r_{0+}^q = r_{012}^q = \frac{r_{01}^q + r_{12}^q e^{2i\beta_1 d_1}}{1 - r_{10}^q r_{12}^q e^{2i\beta_1 d_1}}, \tag{6}$$

here

$$r_{ij}^s = \frac{\mu_j\beta_i - \mu_i\beta_j}{\mu_j\beta_i + \mu_i\beta_j}, \quad r_{ij}^p = \frac{\beta_i\varepsilon_j - \beta_j\varepsilon_i}{\beta_i\varepsilon_j + \beta_j\varepsilon_i}. \tag{7}$$

When we consider the cladding as a perfect conductor, the reflection coefficients γ_{12}^q can be simplified to be $r_{12}^p = 1, r_{12}^s = -1$. From equations (3) and (4) we can see that the inhomogeneity of the medium along the z-axis leads to the Green tensor of the electromagnetic field exhibiting an asymmetric spatial property, i.e., the component along the z-axis is different from those in the x-y-plane. In order to show this spatial inhomogeneity, we assume that the unit vector of the atomic dipole is $\vec{\epsilon} = \frac{1}{\sqrt{2}}(\epsilon_x + i\epsilon_z)$. For the structure under consideration, there exist two kinds of electromagnetic waves in the planar cavity. One is the propagating guided wave whose wave vector obey $0 < k < k_0$, and the other one is the evanescent wave with $k > k_0$. However there is no contribution of the evanescent waves with $k > \sqrt{\varepsilon_1}k_0$ on the atomic spontaneous emission, because these waves cannot propagate out of the atom in our case of ideal metal cladding. Only those with $k_0 < k < \sqrt{\varepsilon_1}k_0$, which formulate evanescent guided modes and propagate in the dielectric layer, affect on atomic spontaneous emission. Nevertheless, it should be emphasized here the evanescent waves with $k > \sqrt{\varepsilon_1}k_0$ will also contribute strongly to the nonradiative decay rate of the atom at the interface of the cavity mirror in the case of real metals [19]. Tomas and Lenac [19] analyzed the decay rate of an excited molecule embedded in a symmetric transparent or absorbing cavity formed by two metallic (Ag) mirrors and the effects of cavity absorption on various contributions to the total molecular decay rate have been revealed. In order to emphasize the effect of the LS on the spontaneous emission rate, here we present a simple example in which we can find the partial evanescent waves at work.

3 Effects of LS of "beams" resulting from atom emissions on spontaneous decay rate

First we consider the propagating guided modes with wave vectors being limited in the region $0 < k < k_0$, the corresponding reflection coefficients to these modes are complex quantities with modulus 1, which can be expressed as $\gamma^p_{0+} = \gamma^p_{0-} = \exp(-i\varphi_p)$, and $\gamma^s_{0+} = \gamma^s_{0-} = \exp(-i\varphi_s)$ $(0 \le \varphi_q \le \pi/2)$. In this region, the imaginary parts of the integrands in equations (3, 4) are zero, apart from resonant when $D_{q0} = 0$ $(q \in p, s)$ is satisfied. For notational simplicity, in the following β_i $(i = 0, 1, 2)$ and k will be re-scaled by k_0, i.e., β_i/k_0 and k/k_0 will be replaced by β_i and k, moreover b and d_i $(i = 0, 1, 2)$ will substitute for bk_0 and d_ik_0. The contributions of the p-polarized guided modes and the s-polarized guided modes to the spontaneous decay rate of the z-component and x-component of the atomic dipole moment are respectively given by

$$\left(\frac{\gamma}{\gamma_0}\right)_{gx} = \frac{3\pi}{4}\left[\sum_m \left|\frac{k\beta_0 \sin^2(\beta_0 b - \frac{\varphi_p}{2})}{(\frac{d_0 k}{\beta_0} + \varphi'_p)}\right|_{k^p_m} + \sum_m \left|\frac{k}{(d_0 k + \beta_0\varphi'_s)}\cos^2\left(\beta_0 b - \frac{\varphi_s}{2}\right)\right|_{k^s_m}\right], \tag{8}$$

$$\left(\frac{\gamma}{\gamma_0}\right)_{gz} = \frac{3\pi}{2}\sum_m \left|\frac{k^3}{\beta_0}\frac{\cos^2(\beta_0 b - \frac{\varphi_p}{2})}{(\frac{d_0 k}{\beta_0} + \varphi'_p)}\right|_{k^p_m}, \tag{9}$$

with

$$\varphi'_s = \frac{2d_1\sqrt{1-\beta_0^2}}{\beta_0}\frac{\beta_0^2 + (\varepsilon_1 - 1)\frac{\sin(2\beta_1 d_1)}{(2\beta_1 d_1)}}{(\beta_0^2 + (\varepsilon_1 - 1)\cos^2(\beta_1 d_1))}$$

denotes $k_0\Delta_s$ (Δ_s is the LS of the "beams" resulting from atom emissions coupled to the s-polarized guided modes by the stationary-phase approximation) and

$$\varphi'_p = \frac{2d_1 k\varepsilon_1}{\beta_0}\frac{\beta_0^2 + (-\varepsilon_1 + 1)\frac{\sin(2\beta_1 d_1)}{(2\beta_1 d_1)}}{(\beta_1^2 + (\beta_0^2\varepsilon_1^2 - \beta_1^2)\cos^2(\beta_1 d_1))}$$

denotes $k_0\Delta_p$ (Δ_p the LS of the "beams" resulting from atom emissions coupled to p-polarized guided modes). The LS mentioned above both refer to the displacement of these reflected "beams" from the path of the geometrical optics at the same interface between layer 0 and layer 1 [15]. γ_0 represents the spontaneous decay rate of the atom in free space. The parameters k^q_m $(m \in (1, 2, \cdots m^q_{max}))$ represent the wave numbers of the mth q-polarized guided modes in the x-y plane, which are the real roots of equation $D_{q0} = 0$ within the region of $0 < k < k_0$. m^q_{max} is the number of modes, which depends on the thickness of the planar cavity and the dielectric layer, the mode polarization, and the permittivity of the dielectric layers. In what follows, for exhibiting the effect of the variation of the LS on the spontaneous decay rate, we will first consider there is only a single mode existing in the planar cavity and analyze the "beams" coupled to p-polarized light mode, the LS of the "beams" coupled to the s-polarized light mode can be discussed similarly. It is seen that the denominator of the expression φ'_p is always positive, and when inequality $\beta_0^2 + (1-\varepsilon_1)\frac{\sin(2\beta_1 d_1)}{2\beta_1 d_1} < 0$ holds, the LS of the "beams" coupled to the p-polarized reflected guided modes is negative. This negative LS is much more easily realized at the large wave number of the p-polarized guided mode in the x-y plane [15]. So it can be easily obtained that the LS can be positive and negative, for example, when we consider the case of $k = \sin 65°$, φ'_p equals -0.988 [dot A in Fig. 2a] at $d_1 = 0.895, d_0 = 1.021$, and equals 1.288 [dot B in Fig. 2a] at $d_1 = 3.023, d_0 = 1.023$. In these two configurations, we can find the LS is the main factor of the variation of the spontaneous emission from the following analysis.

In Figure 3a, we plot the contribution of p-polarized guided mode to the spontaneous emission rate normalized by the free space rate versus the atomic position b. Evidently, the normalized spontaneous decay rate depends on the position of the atom. The spontaneous decay behavior exhibits a symmetric profile with respect to the central plane of the planar cavity for the symmetric models. Since we focus on the effect of the LS of the "beams" resulting from atom emissions on the spontaneous decay rate, we consider only the case of a single mode surviving in the planar cavity. When we choose the above two groups of parameters, the LS is the main factor of the variation of the spontaneous emission as can be seen from equations (8, 9). For concreteness, we find the p-polarized guided mode density of the electromagnetic field with the

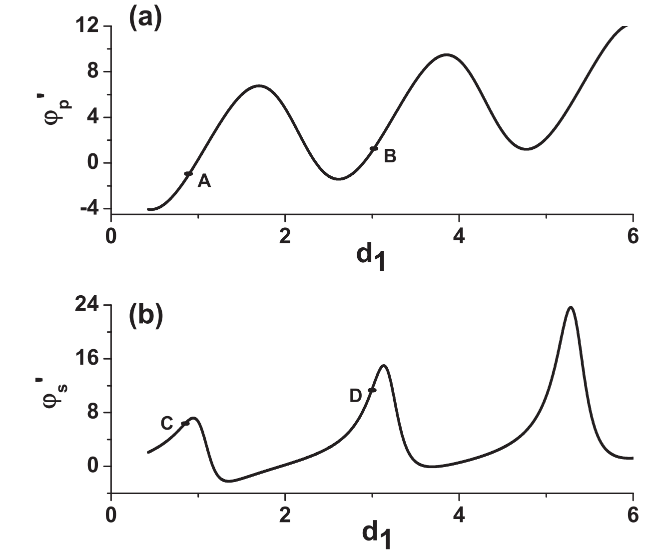

Fig. 2. Dependence of φ_p' (a) and φ_s' (b) on the thickness d_1. Parameters are $\varepsilon_1 = 3.0$ and $k = \sin 65°$.

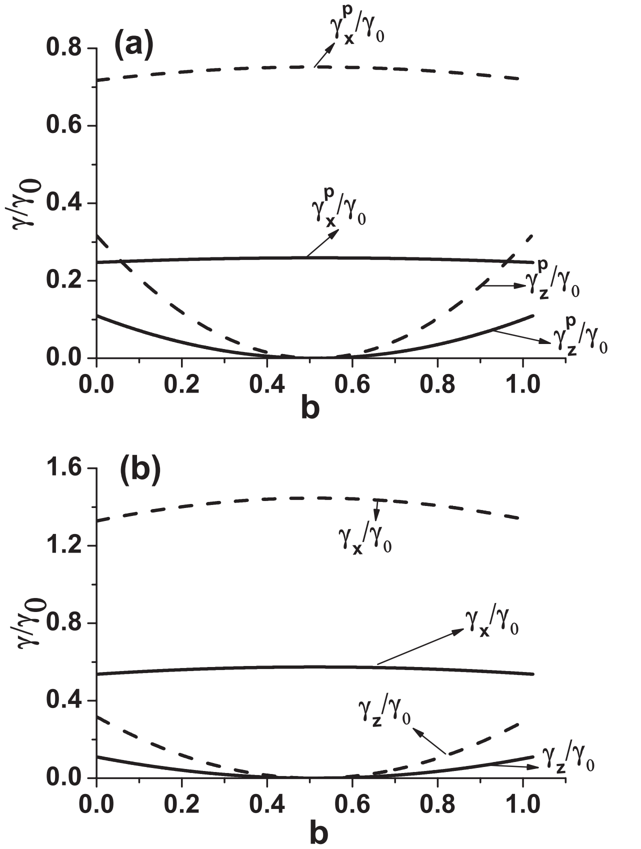

Fig. 3. Dependence of the normalized spontaneous rate of the two components of the atomic dipole moment on the atomic position b with $\varepsilon_1 = 3.0$, $k = \sin 65°$ and $d_1 = 0.895, d_0 = 1.021$ ($\varphi_p' = -0.988$, dashed), $d_1 = 3.023, d_0 = 1.023$ ($\varphi_p' = 1.288$, solid). (a) Involving only the p-polarized mode, (b) involving both the p-polarized mode and the s-polarized mode.

same values of k ($k = \sin 65°$) increase more evidently for the case of dot A than dot B. It is easy to understand that the first term originating from the derivative of the optical path in the denominator of equation (9) is positive (approximately equals 2.19 in the two cases we choose), meanwhile the second term arising from the LS is negative for the case dot A, the summation of the optical path and the LS will be smaller than the case of the positive LS (dot B), and the other terms in the numerator of equation (9) are almost invariant. Here we should emphasize that the spontaneous emission could be evidently modified due to the effect of LS when we choose those two group of different parameters. The first term in equation (8) can be analyzed similarly. It should be pointed out that we don't take into account the case of existing multimode in the planar cavity, because we could not judge the variation of the normalized spontaneous decay rate only results from the effect of LS in that case.

The total normalized spontaneous decay rate involving the contributions of both the p-polarized and s-polarized guided modes is shown in Figure 3b. When the p-polarized guided mode density is enhanced, the s-polarized guided mode density also increases. The main reason of the enhancement is still the effect of LS of the "beams" resulting from atom emissions. Although in our two cases the lateral shifts of the "beams" coupled to the s-polarized mode are both positive, but φ_s' equals 6.907 [dot C in Fig. 2b] at $d_1 = 0.895, d_0 = 1.021$, and equals 12.312 [dot D in Fig. 2b] at $d_1 = 3.023, d_0 = 1.023$. The other terms in the second term of equation (8) are also almost invariant compared with the change of LS. From the above analysis, we know when the thickness of the planar cavity is near some particular values, the mode density will be greatly enhanced by suitably adjusting the thickness of the dielectric layer. Compared with the spontaneous emission rate of the same atom embedded between two conducting plates, owing to introducing the dielectric layer, the summation of the thickness of the planar cavity and the thickness of the dielectric layer for the existence of propagating longitudinal guided modes can be smaller than half of the wavelength and the spontaneous emission rate from the components of the dipole moment parallel to the interfaces of the cavity mirror increases and becomes even larger than from the components of the dipole perpendicular to the interface of the cavity mirror as shown in Figure 3.

Second we analyze the contribution of the evanescent waves with wave vectors obeying $k > k_0$ to the spontaneous emission. We find the imaginary part of the integrands in equations (3) and (4) are zero, apart from resonances when D_{q0} $(q = p, s)$ is satisfied and only when the wave vector are limited in the region $k_0 < k < \sqrt{\varepsilon_1}k_0$, the evanescent guided modes may exist. The contributions of these surface guided modes to the spontaneous decay rate of the two components of the atomic dipole moment are

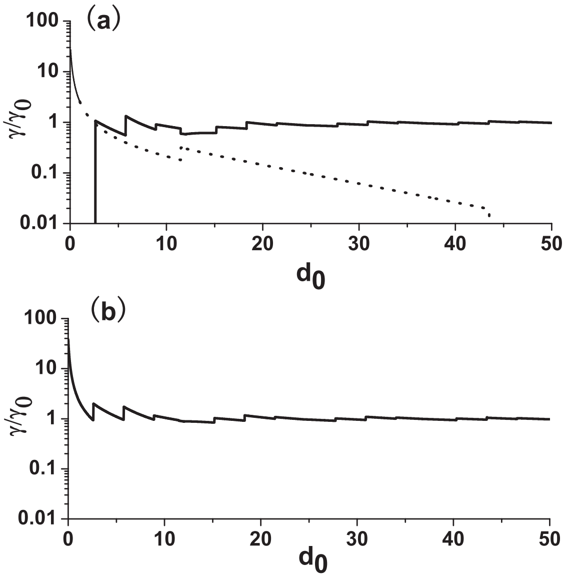

Fig. 4. (a) Dependence of the normalized spontaneous rate respectively from the contributions of the evanescent guided modes (dotted) and the propagating guided modes (solid) on the thickness of the planar cavity d_0 with $\varepsilon_1 = 3.0$, the thickness of the dielectric layer $d_1 = 0.25$ and the atomic position $b = 0.25d_0$. The contribution of the evanescent guided modes and the propagating guided modes are summed to give the total spontaneous rate in (b).

respectively expressed as

$$\left(\frac{\gamma}{\gamma_0}\right)_{sx} = \frac{3\pi}{8}\left[\sum_m \left|\frac{k\beta_0(1 \mp \cosh(-\beta_0 d_0 + 2\beta_0 b)}{(\frac{d_0 k}{\beta_0} - \varphi_p')}\right|_{k_m^p} + \sum_m \left|\frac{k(1 \pm \cosh(-\beta_0 d_0 + 2\beta_0 b)}{\beta_0(\frac{d_0 k}{\beta_0} - \varphi_s')}\right|_{k_m^s}\right], \quad (10)$$

$$\left(\frac{\gamma}{\gamma_0}\right)_{sz} = \frac{3\pi}{4}\sum_m \left|\frac{k^3(1 \pm \cosh(-\beta_0 d_0 + 2\beta_0 b)}{\beta_0(\frac{d_0 k}{\beta_0} - \varphi_p')}\right|_{k_m^p}, \quad (11)$$

where we have set $\beta_0 = \sqrt{k^2 - 1}$, $\gamma_{0+}^p = \gamma_{0-}^p = \pm\exp(\varphi_p)$, and $\gamma_{0+}^s = \gamma_{0-}^s = \pm\exp(\varphi_s)$ $(\varphi_q \geq 0)$. The symbols φ_p' and φ_s' respectively denote the derivatives of φ_p and φ_s. We could obtain the expressions of them by analytical inspection:

$$\varphi_p' = \frac{-2d_1 k\varepsilon_1[\beta_0^2 + (\varepsilon_1 - 1)\frac{\sin(2d_1\beta_1)}{2d_1\beta_1}]}{\beta_0[-\beta_1^2 + \cos^2(\beta_1 d_1)(\beta_1^2 + \beta_0^2\varepsilon_1^2)]},$$

$$\varphi_s' = -\frac{2kd_1[\beta_0^2 + (1 - \varepsilon_1)\frac{\sin(2d_1\beta_1)}{2d_1\beta_1}]}{\beta_0(\beta_0^2 + \cos^2(d_1\beta_1)(1 - \varepsilon_1))}$$

with $\beta_1 = \sqrt{\varepsilon_1 - k^2}$. Different from equations (8) and (9), the mode functions of the surface modes become "cosh" functions instead of the standing wave functions for the propagating guided modes with wave vectors obeying $0 < k < k_0$. When we start from equations (10) and (11), and employ the same method as which we use in the first part, we could also know the effect of the lateral shift of the "beams" coupled to the surface guided modes on the decay rate. The contribution of the surface guided modes to the decay rate could be increased or decreased owing to the change of LS. Here we respectively display the normalized spontaneous decay rate from the contributions of the propagating guided modes and the surface guided modes in respect to the thickness of the planar cavity in Figure 4a and the total decay rate in Figure 4b. When we choose the thickness of the dielectric layer $d_1 = 0.25$ and the atomic position $b = 0.25d_0$, we find the atom can emit stronger evanescent field with wave vectors $k_0 < k < \sqrt{\varepsilon_1}k_0$ propagating out in the x-y plane than the propagating guided field for very thin planar cavity. With the thickness of the planar cavity increasing, the relative spontaneous decay rate may exhibit a sharp cusp at the birth of a surface guided mode which is similar to the behavior of the relative spontaneous decay rate from the contribution of the propagating guided modes, however, when the thickness of the planar cavity exceeds a certain maximum, the decay rate induced by the surface guided modes would decrease to zero, which is different with the decay behavior induced by the propagating guided modes. The reason for the sharp cutoff visible for the dotted curves in Figure 4a is that the absolute values of reflection coefficients exist a maximum and multiply the decaying exponential factor in equation (5) when the wave vectors are limited in the region $k_0 < k < \sqrt{\varepsilon_1}k_0$, so that there is the largest thickness of the planar cavity for satisfying equation (5). We must notice a kink appears in the evanescent guided mode and the propagating guided mode contribution when the thickness of the planar cavity is near the value $11.5/k_0$, which is due to the conversion of propagating guided modes into a new evanescent guided mode. In fact, when $k_0 d_0$ takes the values from 11.5 to 43.2, there are two evanescent guided modes, which is different from the case for $k_0 d_0 < 11.5$, in which there is only one evanescent guided mode. It can be justified in Figure 4b in contrast with Figure 4a. It was found that the similar kinks in the guided-mode and the radiation-mode contribution arise for a three-layer dielectric structure due to the conversion between radiation modes and guided modes [2], but in the present system the appearance of the kink results from the conversion between propagating guided modes and evanescent guided modes.

4 Conclusion

To summarize, after obtaining the expression for the spontaneous decay rate of a two-level atom embedded in a planar cavity with perfect conducting cladding and the lateral shift of the "beams" resulting from atom emissions by the stationary-phase approximation, we have analyzed the effect of lateral shift on spontaneous decay. It has been found that the spontaneous decay can be enhanced or suppressed owing to the positive and negative lateral shift at the interfaces of the cavity mirror. The predicted effects here may have potential improvement in understanding the control of an atomic spontaneous emission by the variation of the environment the atom is placed in. In our structure the surface guided modes could appear and the contribution of these surface guided modes to the decay rate may be greatly larger than the propagating guided modes if the planar cavity is very thin. The conversion between propagating guided modes and evanescent guided modes is shown to exist in our case.

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