Vol 14 No 1, January 2005
1009-1963/2005/14(01)/0144-05

Chinese Physics

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Transmission probability of the two-mode mazer with injected atomic coherence*

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(Received 21 June 2004; revised manuscript received 23 August 2004)

The transmission probability of the two-mode mazer injected with V-type three-level atoms is studied, and the effects of the atomic coherence on it are examined. It is shown that the atomic coherence can affect the transmission probability. In the plots of the atomic transmission probability versus the dimensionless centre-of-mass momentum, there are resonance peaks and non-resonance platforms. The heights of these resonance peaks and non-resonance platforms can be adjusted by the atomic coherence parameter and by the relative coupling strength of the two transition channels.

Keywords: two-mode micromaser, ultracold atoms, atomic coherence
PACC: 4250

1. Introduction

Since it was realized,[1] the micromaser has become one of the most important tools in the study of cavity quantum electrodynamics (cavity QED).[2] The operation of the micromaser has been explained[3,4] and many features of the field in the cavity have been predicted. These include sub-Poissonian statistics,[3,4] the trapping states,[5] and unusual types of diffusion of the field.[6] In recent years, with the development of laser cooling techniques,[7] ultracold atoms have been obtained. When they interact with a quantum electromagnetic field, the quantization of external motion of atoms becomes necessary. This quantization of centre-of-mass (CM) motion[8,9] leads to a completely new kind of induced emission. In this way, a new concept called mazer (microwave amplification via z-motion-induced emission of radiation), introduced by Scully *et al*,[10] has opened a new chapter of micromaser physics.

A complete quantum theory of the mazer was described in a series of three papers by Scully and coworkers.[11−13] The theory was written for two-level atoms interacting with a single mode of the high-Q cavity via a one-photon transition. In particular, it was shown that the induced emission properties were strongly dependent on the cavity mode profile. Results were presented for the mesa, sech^2, and sinusoidal modes. Retamal *et al*[14] later refined these results in the special case of the sinusoidal mode, and a numerical method was proposed by Bastin *et al*[15] for efficiently computing the mazer properties with arbitrary cavity field modes. Löffler *et al*[16] showed also that the mazer could be used as a velocity selection device for an atomic beam. The mazer concept was extended by Zhang *et al*,[17−20] who considered two-photon transitions,[17] and three-level atoms interacting with a single cavity[18,19] and with two cavities.[20] Collapse and revival patterns with a mazer have been computed by Du *et al*.[21] Arun *et al*[22,23] and Liang *et al*[24] studied the mazer with bimodal cavities. Agarwal and Arun[25] demonstrated resonant tunnelling of cold atoms through two mazer cavities. Wu *et al*[26] studied the atomic emission probability and photon statistics of the micromaser with Kerr medium. Recently, atomic coherence in the mazer system has been studied by Zhang *et al*[27] and they found that the atomic coherence could modify the atomic emission probability and the photon statistics. Liang *et al*[24] studied the properties of the two-mode mazer operating on V-type three-level atoms, but in their paper the transmission probability was not studied and the atomic coherence was not considered, either. In the present paper, we study transmission probability of the two-mode mazer operating on V-type three-level

*Project supported by the National Natural Science Foundation of China (Grant Nos 60178001 and 10074046).
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atoms with the effects of atomic coherence considered.

The organization of the paper is as follows. In Section 2, we derive the general expression for the transmission probability of the V-type three level cold atoms moving through the two-mode cavity, with atomic coherence taken into account. In Section 3, we study the transmission probability of one atom through the mazer using the general expression. Section 4 is our conclusions.

2. General theory of the transmission probability

We study the V-type three-level cold atoms (with $|a\rangle$ and $|b\rangle$ the two upper levels, and $|c\rangle$ the lower level) passing through a high Q, two-mode microwave cavity of length l as given by Liang *et al.*[24] In a suitable reference frame, the Hamiltonian of the atom–field system reads as

$$\begin{aligned} H &= \frac{p_z^2}{2M} + u(z)V, \\ V &= \hbar(g_1|a\rangle\langle c|a_1 + g_2|b\rangle\langle c|a_2 + \text{H.c.}), \end{aligned} \tag{1}$$

where M is the atomic mass, p_z the atomic momentum operator for the CM motion and $u(z)$ is the mode function of the cavity field. The parameter $g_1(g_2)$ is the coupling strength of the transition $|a\rangle \leftrightarrow |c\rangle(|b\rangle \leftrightarrow |c\rangle)$ with cavity mode 1 (2). The operator V is readily diagonalizable. It has eigenstates $|\phi^0_{n_1+1,n_2+1}\rangle$, $|\phi^{\pm}_{n_1+1,n_2+1}\rangle$ with eigenvalues 0, $\pm\hbar\Omega_{n_1+1,n_2+1}$, respectively, where

$$\begin{aligned} |\phi^j_{n_1+1,n_2+1}\rangle =& \alpha^{(j)}_{n_1+1,n_2+1}|a, n_1, n_2+1\rangle \\ &+ \beta^{(j)}_{n_1+1,n_2+1}|b, n_1+1, n_2\rangle \\ &+ \gamma^{(j)}_{n_1+1,n_2+1}|c, n_1+1, n_2+1\rangle) \\ & (j = 0, \pm), \end{aligned} \tag{2}$$

in which

$$\begin{aligned} \alpha^{(0)}_{n_1,n_2} &= \frac{d_{2,n_2}}{\Omega_{n_1,n_2}}, \\ \beta^{(0)}_{n_1,n_2} &= -\frac{d_{1,n_1}}{\Omega_{n_1,n_2}}, \\ \gamma^{(0)}_{n_1,n_2} &= 0, \\ \alpha^{(\pm)}_{n_1,n_2} &= \frac{d_{1,n_1}}{\sqrt{2}\Omega_{n_1,n_2}}, \\ \beta^{(\pm)}_{n_1,n_2} &= \frac{d_{2,n_2}}{\sqrt{2}\Omega_{n_1,n_2}}, \\ \gamma^{(\pm)}_{n_1,n_2} &= \pm\frac{1}{\sqrt{2}}. \end{aligned} \tag{3}$$

Here $\Omega_{n_1,n_2} = \sqrt{d^2_{1,n_1} + d^2_{2,n_2}}$, $d_{1,n_1} = g_1\sqrt{n_1}$, $d_{2,n_2} = g_2\sqrt{n_2}$. We now consider the problem that an atom in the superposition state $(C_a|a\rangle + C_b|b\rangle)$ with a CM wave packet $\psi(z)$ is incident upon a cavity field with n_1 photons in mode 1 and n_2 photons in mode 2. As discussed in Refs.[10,11,17–19], this problem can be treated as a scattering process. The state of the atom–field system before the scattering process is

$$\begin{aligned} \langle z|\psi(0)\rangle =& \psi(z,0)(C_a|a, n_1, n_2\rangle + C_b|b, n_1, n_2\rangle) \\ =& \psi(z,0)\sum_{j=0,\pm}(C_a\alpha^{(j)}_{n_1+1,n_2}|\phi^{(j)}_{n_1+1,n_2}\rangle \\ &+ C_b\beta^{(j)}_{n_1,n_2+1}|\phi^{(j)}_{n_1,n_2+1}\rangle), \end{aligned} \tag{4}$$

with $\psi(z,0) = \int \mathrm{d}kA(k)\mathrm{e}^{\mathrm{i}kz}\theta(-z)$. Here $C_a = \cos\theta$, $C_b = \mathrm{e}^{\mathrm{i}\phi}\sin\theta$, θ and ϕ are the atomic coherence parameters, and Heaviside's unit step function $\theta(-z)$ merely indicates on which side of the cavity the atom can be found. We denote the reflection and transmission amplitudes by $\rho^{(\pm)}_{n_1+1,n_2+1}$, $\tau^{(\pm)}_{n_1+1,n_2+1}$ for the potential barrier-well problem of the dressed states $|\phi^{\pm}_{n_1+1,n_2+1}\rangle$, respectively. The state of the system after the interaction reads as

$$\begin{aligned} \langle z|\psi(\tau)\rangle =& \int \mathrm{d}kA(k)\mathrm{e}^{-\mathrm{i}\frac{\hbar k^2}{2M}\tau} \\ &\times \{\mathrm{e}^{\mathrm{i}k(z-l)}\theta(z-l)C_a\alpha^{(0)}_{n_1+1,n_2}|\phi^{(0)}_{n_1+1,n_2}\rangle \\ &+ [\rho^{(+)}_{n_1+1,n_2}\mathrm{e}^{-\mathrm{i}kz}\theta(-z) + \tau^{(+)}_{n_1+1,n_2} \\ &\times \mathrm{e}^{\mathrm{i}k(z-l)}\theta(z-l)]C_a\alpha^{(+)}_{n_1+1,n_2}|\phi^{(+)}_{n_1+1,n_2}\rangle \\ &+ [\rho^{(-)}_{n_1+1,n_2}\mathrm{e}^{-\mathrm{i}kz}\theta(-z) + \tau^{(-)}_{n_1+1,n_2} \\ &\times \mathrm{e}^{\mathrm{i}k(z-l)}\theta(z-l)]C_a\alpha^{(-)}_{n_1+1,n_2}|\phi^{(-)}_{n_1+1,n_2}\rangle \\ &+ \mathrm{e}^{\mathrm{i}k(z-l)}\theta(z-l)C_b\beta^{(0)}_{n_1,n_2+1}|\phi^{(0)}_{n_1,n_2+1}\rangle \\ &+ [\rho^{(+)}_{n_1,n_2+1}\mathrm{e}^{-\mathrm{i}kz}\theta(-z) + \tau^{(+)}_{n_1,n_2+1} \\ &\times \mathrm{e}^{\mathrm{i}k(z-l)}\theta(z-l)]C_b\beta^{(+)}_{n_1,n_2+1}|\phi^{(+)}_{n_1,n_2+1}\rangle \\ &+ [\rho^{(-)}_{n_1,n_2+1}\mathrm{e}^{-\mathrm{i}kz}\theta(-z) + \tau^{(-)}_{n_1,n_2+1} \\ &\times \mathrm{e}^{\mathrm{i}k(z-l)}\theta(z-l)]C_b\beta^{(-)}_{n_1,n_2+1}|\phi^{(-)}_{n_1,n_2+1}\rangle\}, \end{aligned} \tag{5}$$

where τ is the interaction time.

From the final state (5), which clearly shows the reflection and transmission of each dressed component after the interaction, we obtain the total transmission probability as follows:

$$\begin{aligned} P_{\text{trans}}(n_1,n_2) =& |C_a\alpha^{(0)}_{n_1+1,n_2}|^2 + |\tau^{(-)}_{n_1+1,n_2}C_a\alpha^{(-)}_{n_1+1,n_2}|^2 \\ &+ |\tau^{(+)}_{n_1+1,n_2}C_a\alpha^{(+)}_{n_1+1,n_2}|^2 \\ &+ |C_b\beta^{(0)}_{n_1,n_2+1}|^2 + |\tau^{(-)}_{n_1,n_2+1}C_b\beta^{(-)}_{n_1,n_2+1}|^2 \\ &+ |\tau^{(+)}_{n_1,n_2+1}C_b\beta^{(+)}_{n_1,n_2+1}|^2. \end{aligned} \tag{6}$$

The above theory is rather general so that it is suitable to the arbitrary mode functions. In the following, we approximate the mode function of the cavity by the mesa function $u(z)=1$ for $0<z<l$ and zero elsewhere, and the reflection $\rho^{(\pm)}_{n_1,n_2}$ and transmission $\tau^{(\pm)}_{n_1,n_2}$ amplitudes can be calculated analytically,

$$\begin{aligned}
&\rho^{(\pm)}_{n_1,n_2}=\mathrm{i}\Delta^{(\pm)}_{n_1,n_2}\sin(k^{(\pm)}_{n_1,n_2}l)\tau^{(\pm)}_{n_1,n_2},\\
&\tau^{(\pm)}_{n_1,n_2}=[\cos(k^{(\pm)}_{n_1,n_2}l)-\mathrm{i}\sum\nolimits^{(\pm)}_{n_1,n_2}\sin(k^{(\pm)}_{n_1,n_2}l)]^{-1},\\
&k^{(\pm)}_{n_1,n_2}=\sqrt{k^2\mp k^2_{n_1,n_2}},\\
&\Delta^{(\pm)}_{n_1,n_2}=\frac{1}{2}\left(\frac{k^{(\pm)}_{n_1,n_2}}{k}-\frac{k}{k^{(\pm)}_{n_1,n_2}}\right),\\
&\sum\nolimits^{(\pm)}_{n_1,n_2}=\frac{1}{2}\left(\frac{k^{(\pm)}_{n_1,n_2}}{k}+\frac{k}{k^{(\pm)}_{n_1,n_2}}\right),\\
&k_{n_1,n_2}=\sqrt{2M\Omega_{n_1,n_2}}=\kappa\sqrt[4]{\frac{g_1^2n_1+g_2^2n_2}{g_1^2+g_2^2}},
\end{aligned}\tag{7}$$

where $\hbar k$ is the atomic CM momentum and κ is defined with $(\hbar\kappa)^2/2M=\hbar\sqrt{g_1^2+g_2^2}$.

For simplicity, we introduce the following dimensionless quantities:

$$\begin{aligned}
&r_{n_1,n_2}=k_{n_1,n_2}/\kappa=\sqrt[4]{\frac{g_1^2n_1+g_2^2n_2}{g_1^2+g_2^2}},\quad r=k/\kappa,\\
&r^{(\pm)}_{n_1,n_2}=k^{(\pm)}_{n_1,n_2}/\kappa=\sqrt{r^2\mp r^2_{n_1,n_2}},\quad L=\kappa l.
\end{aligned}\tag{8}$$

In this paper, we restrict ourselves to the ultracold atom case, i.e. the case in which the kinetic energy of the incident atom is much smaller than the atom–field coupling energy ($k\ll k_{n_1,n_2}$).[18,24] In this situation, tunnelling through the potential barrier is negligible, i.e. $\rho^{(+)}_{n_1,n_2}\approx-1$ and $\tau^{(+)}_{n_1,n_2}\approx0$. When the atom encounters a potential well, it is reflected for $k_{n_1,n_2}l\neq m\pi$ (m is an integer) (i.e. $\rho^{(-)}_{n_1,n_2}\approx-1$ and $\tau^{(-)}_{n_1,n_2}\approx0$) and is transmitted for $k_{n_1,n_2}l=m\pi$ (i.e. $\rho^{(-)}_{n_1,n_2}\approx0$ and $\tau^{(-)}_{n_1,n_2}\approx(-1)^m\mathrm{e}^{-\mathrm{i}kl}$), so

$$\begin{aligned}
&|\tau^{(+)}_{n_1,n_2}|^2\approx0,\\
&|\tau^{(-)}_{n_1,n_2}|^2=\frac{1}{1+(\Delta^{(-)}_{n_1,n_2})^2\sin^2(r^{(-)}_{n_1,n_2}L)},
\end{aligned}\tag{9}$$

where

$$\Delta^{(-)}_{n_1,n_2}=\frac{1}{2}\left(\frac{r^{(-)}_{n_1,n_2}}{r}-\frac{r}{r^{(-)}_{n_1,n_2}}\right).\tag{10}$$

3. Transmission probability of one atom through the mazer

From Eqs.(3), (7) and (9), the transmission (6) can be reduced to

$$\begin{aligned}
P_{\mathrm{trans}}(n_1,n_2)=&\left[1+\frac{g_1^2(n_1+1)}{g_2^2n_2}\right]^{-1}\cos^2(\theta)\\
&+\left[1+\frac{g_2^2(n_2+1)}{g_1^2n_1}\right]^{-1}\sin^2(\theta)\\
&+\frac{\cos^2(\theta)}{2\left[1+\dfrac{g_2^2n_2}{g_1^2(n_1+1)}\right]}\\
&\times[1+(\Delta^{(-)}_{n_1,n_2})^2\sin^2(r^{(-)}_{n_1,n_2}L)]^{-1}\\
&+\frac{\sin^2(\theta)}{2\left[1+\dfrac{g_1^2n_1}{g_2^2(n_2+1)}\right]}\\
&\times[1+(\Delta^{(-)}_{n_1,n_2})^2\sin^2(r^{(-)}_{n_1,n_2}L)]^{-1}.
\end{aligned}\tag{11}$$

From Eq.(11), we can find the essential features of the transmission probability versus r. The first and second terms on the right-hand side in the above equation depend on the parameters θ, g_1, g_1, n_1, n_2, but not on r, so it is a uniform background, coming from the $|\phi^0\rangle$ component which meets a zero potential, and the third and the last terms are a series of resonant peaks, which come from the $|\phi^{(-)}\rangle$ component which sees a deep square potential well. When $n_1=0$ and $n_2=0$, that is the cavity is initially in the vacuum state, the transmission probability reduces to

$$P_{\mathrm{trans}}(n_1,n_2)\simeq\frac{1}{2}[1+(\Delta^{(-)}_{n_1,n_2})^2\sin^2(r^{(-)}_{n_1,n_2}L)]^{-1}.\tag{12}$$

For $n_1\neq0$ or $n_2\neq0$, the numerical calculations of P_{trans} versus r are shown in Fig.1. From the figure, we can see that the transmission probability versus r is a series of very sharp resonant peaks superposed on a uniform background. For simplicity, we call the uniform background the non-resonance platform.

3.1. Positions of the peaks and the spaces between them

From the resonant condition $r^{(-)}_{n_1,n_2}L=m\pi$ (m is an integer), we have

$$r=\left[\left(\frac{m\pi}{L}\right)^2-\left(\frac{g_1^2n_1+g_2^2n_2}{g_1^2+g_2^2}\right)^{1/2}\right]^{1/2},\tag{13}$$

which indicates that the positions and the spaces depend on m, L, n_1, n_2, g_1 and g_2, but not on the atomic coherence parameters. Since $r>0$, m must satisfy $m>L/\pi\left(\dfrac{g_1^2n_1+g_2^2n_2}{g_1^2+g_2^2}\right)^{1/4}$. With the parameters $L=10^4$, $g_1/g_2=1$, $n_1=0$, $n_2=1$, we obtain $m\geq2677$. The values of m and r for several peaks

are given in Table 1. We note that the peaks become closer as r increases. This is in good agreement with Fig.1(a).

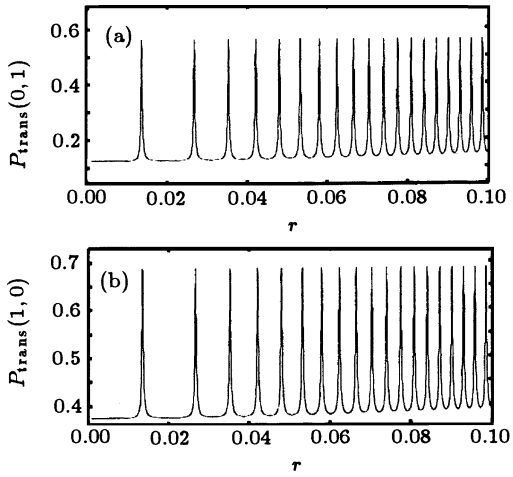


Fig.1. The transmission probability $P_{\rm trans}$ versus the dimensionless CM momentum r for the parameters $L = 10^4$, $g_1 = g_2$, $\theta = \pi/3$, and (a) $n_1 = 0$, $n_2 = 1$, (b)$n_1 = 1$, $n_2 = 0$.

Table 1. Values of m and r for several peaks.

m_i	r_i	$(r_i - r_{i-1})$
2677	0.0135	–
2678	0.0266	0.0132
2679	0.0352	0.0085
2680	0.0420	0.0068
2681	0.0479	0.0059
2682	0.0532	0.0052

3.2. Heights of the peaks and the platform

From the above discussions, we know that the transmission probability versus r is the superposition of a series of peaks on the platform. In order to obtain the heights of the peaks and the platform, we use $\tau^{(\pm)}_{n_1,n_2}$ as discussed in Section 2, then the transmission probability Eq.(11) can be reduced to

$$P_{\rm trans}(n_1,n_2) = \begin{cases} P^{\rm off}_{\rm trans} = \dfrac{1}{1+\dfrac{g_1^2(n_1+1)}{g_2^2 n_2}}\cos^2(\theta) + \dfrac{1}{1+\dfrac{g_2^2(n_2+1)}{g_1^2 n_1}}\sin^2(\theta), & r^{(-)}_{n_1,n_2}L \neq m\pi, \\ P^{\rm on}_{\rm trans} = P^{\rm off}_{\rm trans} + \dfrac{\cos^2(\theta)}{2}\left[1+\dfrac{g_2^2 n_2}{g_1^2(n_1+1)}\right]^{-1} & \\ \qquad + \dfrac{\sin^2(\theta)}{2}\left[1+\dfrac{g_1^2 n_1}{g_2^2(n_2+1)}\right]^{-1}, & r^{(-)}_{n_1,n_2}L = m\pi. \end{cases}$$

Here $P^{\rm on}_{\rm trans}$ and $P^{\rm off}_{\rm trans}$ are the heights of the resonance peaks and the non-resonance platform, as shown in Fig.1. Now we discuss the effects of θ on the heights of the peaks and the platforms of the transmission probability.

When $\sin^2(\theta)$ is equal to 0 or 1, the action of atomic coherence disappears, reducing into a two-mode V-type three-level mazer without coherence. We also consider two different cases of cavity field in Fig.1. One is $|0,1\rangle$, the other is $|1,0\rangle$. The transmission probability is

$$P_{\rm trans}(n_1,n_2) = \begin{cases} P^{\rm off}_{\rm trans} = \dfrac{g_2^2}{g_1^2+g_2^2}\cos^2(\theta), & r^{(-)}_{n_1,n_2}L \neq m\pi, \\ P^{\rm on}_{\rm trans} = P^{\rm off}_{\rm trans} + \dfrac{g_1^2}{2(g_1^2+g_2^2)}\cos^2(\theta) + \dfrac{1}{2}\sin^2(\theta), & r^{(-)}_{n_1,n_2}L = m\pi, \end{cases}$$

for $|0,1\rangle$, and is

$$P_{\rm trans}(n_1,n_2) = \begin{cases} P^{\rm off}_{\rm trans} = \dfrac{g_1^2}{g_1^2+g_2^2}\sin^2(\theta), & r^{(-)}_{n_1,n_2}L \neq m\pi, \\ P^{\rm on}_{\rm trans} = P^{\rm off}_{\rm trans} + \dfrac{g_2^2}{2(g_1^2+g_2^2)}\sin^2(\theta) + \dfrac{1}{2}\cos^2(\theta), & r^{(-)}_{n_1,n_2}L = m\pi, \end{cases}$$

for $|1,0\rangle$.

From Fig.2 we see that the injected atomic coherence can modify the heights of the resonance peak and the non-resonance platform. The ratio g_1/g_2 can also modify them, as shown in Fig.3.

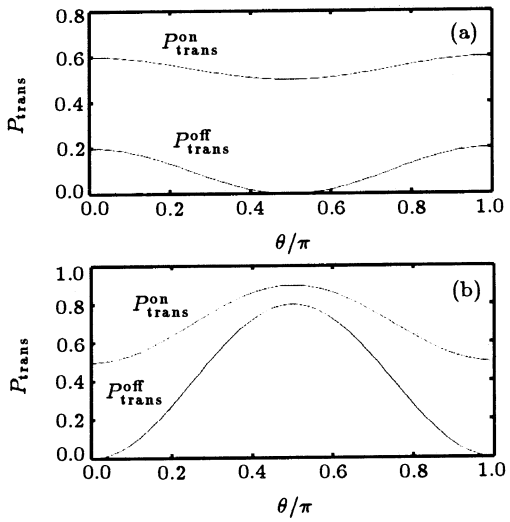


Fig.2. The transmission probability $P_{\rm trans}$ versus θ for the parameters $g_1/g_2 = 2$, and (a) $n_1 = 0$, $n_2 = 1$, (b) $n_1 = 1$, $n_2 = 0$.

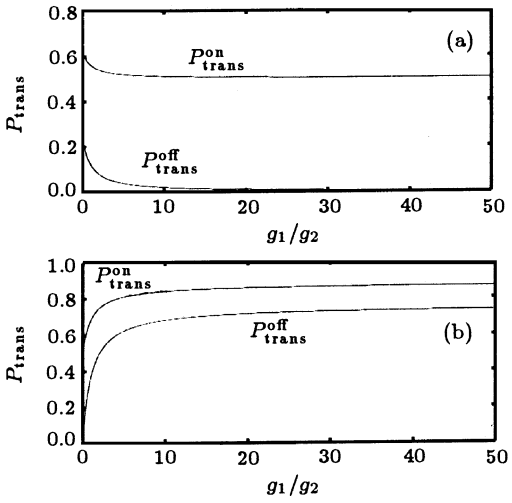


Fig.3. The transmission probability $P_{\rm trans}$ versus g_1^2/g_2^2 for the parameters $\theta = \pi/3$, and (a) $n_1 = 0$, $n_2 = 1$, (b) $n_1 = 1$, $n_2 = 0$.

4. Conclusion

We have studied the transmission probability of the two-mode micromaser pumped by the cold V-type three-level atoms, with the atomic coherence considered. In the plots of the atomic transmission probability vs the dimensionless CM momentum r, there are resonance peaks and non-resonance platforms, and their heights can be modified by the atomic coherence parameter θ and by the relative coupling strength of the two transition channels g_1/g_2. According to the features of the transmission probability we expect that the mazer system discussed in this paper can be used as a velocity selection device for three-level atoms, just as the two-level-atom mazer can be used to select the velocity of two-level atoms.

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