



拉盖尔-高斯旋振腔内原子系综的光力学调控特性

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摘要 腔光力学不仅是探索量子物理新现象的重要平台, 还是下一代精密测量、量子信息技术和新型功能器件开发的技术引擎. 本文通过求解海森堡-朗之万方程, 研究了嵌入原子系综的拉盖尔-高斯旋振腔系统的光力学特性. 研究发现, 由于腔场分别跟原子系综以及旋振镜耦合, 使得探测场吸收谱中双光子诱导透明(Optomechanically Induced Transparency, OMIT)和电磁感应透明(Electromagnetically Induced Transparency, EIT)窗口共存, 而原子系综与腔场的耦合还将引起吸收增益现象. 调节原子系综的原子数目和泵浦场的功率, 能够分别实现对EIT窗口和OMIT窗口的深度和宽度的调控; 改变腔场的衰减率则可以对吸收谱的峰值强度进行调控; 改变腔模拓扑荷数可调控旋转模式对应的OMIT窗口深度和宽度. 通过调节腔模与泵浦场之间的有效失谐以及原子系综与泵浦场之间的失谐, 可以使吸收谱呈现出不对称的多重法诺共振, 并实现对输出场能量在透射、反射和吸收通道间的灵活调控.

关键词 拉盖尔-高斯旋振腔, 原子系综, 电磁感应透明, 光子诱导透明, 法诺共振

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1 引言

电磁诱导透明(Electromagnetically Induced Transparency, EIT)^[1-4]是多能级原子在强场作用下, 共振吸收峰处出现透明窗口的量子干涉现象. 1991年Boller等人^[1]首次在原子蒸汽实验^[2]中观察到EIT, 目前EIT已经成为一种普遍的相干控制方法, 是量子光学领域许

多技术突破的基础, 在量子储存^[5-7]、克尔非线性增强^[8]、光开关^[9]以及振子冷却^[10]等方面具有重要应用.

腔光力学^[11]作为研究光场与力学谐振子相互作用的学科, 通过光辐射压耦合实现光学模式和宏观力学模式的量子操控^[12-14]. 腔光力学在发展过程中产生了许多有趣的量子现象, 如法诺共振^[15-17]、边带冷却^[18-21]、光子诱导吸收^[22]、量子纠缠^[23-27]、光子诱

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导透明(Optomechanically Induced Transparency, OMIT)^[28-31]等现象. 其中OMIT引起人们极大关注, 其物理机制是腔光力学系统在强泵浦场驱动下系统内部不同路径之间产生相消干涉, 从而在探测场强吸收区域产生透明窗口^[32,33]. OMIT现象在快慢光^[34-36]、振子基态冷却^[37]、声子激光^[38,39]、量子传感器技术^[40]、原子局域化的精确测量^[41,42]、引力波探测^[43-45]、量子信息处理^[46-48]等领域得到广泛应用.

法布里-珀罗(Fabry-Perot, F-P)腔是典型的腔光力学系统, 其由一面固定镜和一面在平衡位置自由移动的振动镜平行放置组成. 近年来, 研究者在传统F-P腔基础上, 通过引入螺旋相位片构建了拉盖尔-高斯(Laguerre-Gauss, L-G)旋振腔光力学系统, 实现了腔场与轨道角动量之间的光旋转耦合. 这类耦合体系为角动量的量子操控及拓扑光子学相关研究提供了新的实验平台^[49]. 已有研究显示, L-G旋振腔系统的探测吸收谱中可呈现两个独立的OMIT透明窗口^[50], 印证了其在光学透明窗口调控方面具有独特优势. 在原子辅助腔光力学系统中, 原子的集体激发通过腔修饰作用转化为极化激元, 从而诱导原子与腔镜之间的有效耦合^[51]. 这种原子-腔杂化系统也引起了广泛的研究兴趣, 例如原子辅助F-P腔中EIT-OMIT混合透明探索^[52]、基于L-G旋转腔与原子系综的腔光力学系统纠缠特性研究^[53]以及原子系综对双L-G转动腔中OMIT效应的调控^[54]等.

本文将对嵌入原子系综的L-G旋转振动腔的光力学行为进行研究, 综合考虑腔场与旋振镜间的光旋转及光辐射压耦合、腔场与原子系综耦合、腔场与强泵浦场和弱探测场的相互作用, 研究体系中混合EIT与OMIT窗口的产生和调控机制, 在此基础上, 进一步系统分析原子系综与腔场集体耦合强度、泵浦场功率、拓扑荷数、腔模与泵浦场的有效失谐以及原子跃迁与泵浦场之间的失谐等因素对系统光力学响应的调控规律.

2 物理模型与理论方法

考虑如图1所示的腔光力学系统, 是由两个螺旋相位片平行放置的L-G旋振腔, 腔长为 L , 左侧螺旋相位片固定, 不改变透射光束的轨道角动量, 仅对反射光束附加 $2l$ 的拓扑荷数; 右侧螺旋相位片可沿腔轴旋转与

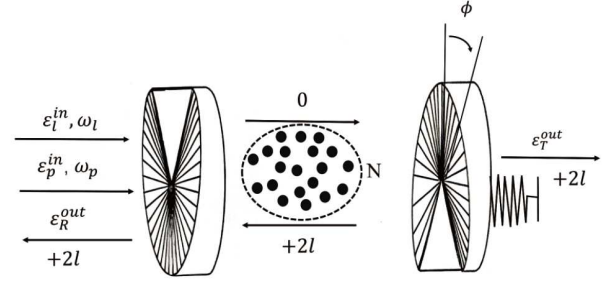


图1 由强泵浦场 ϵ_l^{in} 和弱探测场 ϵ_p^{in} 驱动的旋振腔示意图. N 个相同的二能级原子被束缚在腔内. 反射振幅和透射振幅分别为 ϵ_R^{out} 和 ϵ_T^{out} .

Figure 1 Schematic diagram of a rovibrational cavity driven by a strong pump field ϵ_l^{in} and probed by a weak field ϵ_p^{in} . N is the number of atoms confined in the cavity. The reflection and transmission amplitudes are denoted as ϵ_R^{out} and ϵ_T^{out} .

振动, 对透射光束和反射光束均附加 $2l$ 的拓扑荷. 腔内束缚着频率为 ω_a 的 N 个相同二能级原子, 因此可通过改变原子数目调节原子系综与腔场之间的集体耦合强度^[55], 系统由外加频率 ω_l 的强泵浦场和 ω_p 的弱探测场驱动. $\epsilon_l^{\text{in}} = \sqrt{P_l / \hbar \omega_l}$ ($\epsilon_p^{\text{in}} = \sqrt{P_p / \hbar \omega_p}$) 表示泵浦场(探测场)振幅强度, P_l (P_p) 是泵浦场(探测场)功率. 设外场与腔的振幅输入耦合系数为 $\kappa_{\text{ex}} = \eta_c \kappa$, 大小由输入光场通过左侧输入镜时的耗散决定, 其中 κ 是腔场总的振幅衰减率, 耦合参数 η_c 可以连续调节, 则耦合进腔内的泵浦场(探测场)强度 $\epsilon_l = \epsilon_l^{\text{in}} \sqrt{2\kappa_{\text{ex}}}$ ($\epsilon_p = \epsilon_p^{\text{in}} \sqrt{2\kappa_{\text{ex}}}$). 图1所示的腔光力学系统总的哈密顿量为

$$\begin{aligned} \hat{H} = & \hbar \omega_c c^\dagger c + \frac{1}{2} \left(\frac{p_z^2}{m} + m \omega_z^2 q^2 \right) \\ & - \hbar g_z c^\dagger c q + \frac{1}{2} \left(\frac{L_z^2}{I} + I \omega_\phi^2 \phi^2 \right) \\ & - \hbar g_\phi c^\dagger c \phi + \frac{\hbar}{2} \omega_a \sum_{i=1}^N \sigma_z^i + \hbar g \left(c \sum_{i=1}^N \sigma_+^i + c^\dagger \sum_{i=1}^N \sigma_-^i \right) \\ & + i \hbar \left[(\epsilon_l e^{-i\omega_l t} + \epsilon_p e^{-i\omega_p t}) c^\dagger - H c \right], \end{aligned} \quad (1)$$

其中第一项表示L-G单模腔场(共振频率 ω_c)的自由哈密顿量, 第二项表示振动模式(频率 ω_z)的自由哈密顿量, 第三项表示腔场与旋振镜之间的光辐射压耦合, 第四项表示旋振镜转动模式(频率 ω_ϕ)的自由哈密顿量, 第五项表示腔场与旋振镜之间的光旋转耦合, 第六项表示系统中原子系综的自由哈密顿量, 第七项表示腔场与原子系综之间的相互耦合项, 最后一项表示腔场

与强泵浦场和弱探测场之间的相互作用. 式(1)中, p 和 q 分别表示旋振镜的动量和位移; L_z 和 ϕ 分别表示旋振镜的角动量和角位移; $I=mr^2/2$ 表示旋振镜关于腔轴的转动惯量, 其中 m 为旋振镜质量, r 为旋振镜半径. $g_\phi=c\ell/L$ ($g_z=\omega_c/L$)描述光子和旋振镜之间的光旋转(光辐射压)耦合强度, 其中 c 是真空光速, ℓ 表征拓扑荷数; ω_a 代表原子在基态 $|0\rangle$ 与激发态 $|1\rangle$ 之间的跃迁频率. σ_+^i 和 σ_-^i 分别表示第 i 个原子的上升与下降算符, 满足对易关系 $[\sigma_+^i, \sigma_-^i] = \sigma_z^i$, N 是原子数目, 考虑原子系综有大量原子 $N \gg 1$, 我们可以用Holstein-Primakoff变换^[56]描述, 在低原子激发极限下, 原子系综的集体升降算符表示为 $a^\dagger = \left[\sum_{i=1}^N \sigma_+^i \right] / \sqrt{N}$, $a = \left[\sum_{i=1}^N \sigma_-^i \right] / \sqrt{N}$. $g = \mu\sqrt{\omega_c(2\hbar c_0 V)}$ 为腔场与单原子耦合强度, 其中 μ 为原子跃迁偶极矩, V 为腔场有效体积. 式(1)中各算符满足以下对易关系: $[c, c^\dagger] = 1$, $[a, a^\dagger] = 1$, $[q, p] = i\hbar$, $[\phi, L_z] = i\hbar$.

任意算符 $\hat{A}$ 满足海森堡方程 $\dot{\hat{A}} = i[\hat{H}, \hat{A}] / \hbar$. 对式(1)采用平均场近似 $\langle c^\dagger c \rangle = \langle c^\dagger \rangle \langle c \rangle$, 同时考虑系统耗散引起的旋振镜衰减和腔场衰减, 在由泵浦场频率 ω_l 定义的旋转框架变换 $\hat{A} = \tilde{A} e^{i\omega_l t}$ 下, 可以得到系统各算符 $\tilde{A}$ 随时间演化的海森堡-朗之万方程:

$$\begin{aligned} \langle \dot{\phi} \rangle &= \frac{\langle L_z \rangle}{I}, \\ \langle \dot{L}_z \rangle &= \hbar g_\phi \langle c^\dagger \rangle \langle c \rangle - I\omega_\phi^2 \langle \phi \rangle - \gamma_\phi \langle L_z \rangle, \\ \langle \dot{q} \rangle &= \frac{\langle p \rangle}{m}, \\ \langle \dot{p} \rangle &= \hbar g_z \langle c^\dagger \rangle \langle c \rangle - m\omega_z^2 \langle q \rangle - \gamma_z \langle p \rangle, \\ \langle \dot{c} \rangle &= \varepsilon_l - \left[\kappa + i(\Delta_c - g_\phi \langle \phi \rangle - g_z \langle q \rangle) \right] \langle c \rangle \\ &\quad + \varepsilon_p e^{-i\Delta_p t} - ig \langle a \rangle \sqrt{N}, \\ \langle \dot{a} \rangle &= -(\gamma_a + i\Delta_a) \langle a \rangle - ig \langle c \rangle \sqrt{N}, \end{aligned} \quad (2)$$

式中 $\gamma_z(\gamma_\phi)$ 是旋振镜振动(转动)弛豫速率, $g\sqrt{N}$ 是原子系综和腔场的集体耦合强度, $\Delta_p = \omega_p - \omega_l$ 是探测场和泵浦场的失谐, γ_a 是原子弛豫速率, $\Delta_c = \omega_c - \omega_l$ 表示腔模与泵浦场之间的失谐, $\Delta_a = \omega_a - \omega_l$ 表示原子系综与泵浦场之间的失谐.

对式(2)中各物理量算符平均值采用线性化分析, 假设 $\langle A \rangle = A_s + \delta A$ ^[57-59], 其中 A_s 为算符 A 的稳态值, δA 为算符涨落强度平均值. 由于探测场扰动较弱($\varepsilon_p \ll \varepsilon_l$), 在对式(2)中各物理量进行稳态值 A_s 求解时, 先不考虑探测场作用. 在线性化条件下, 得到各动力学变量的稳态值分别为

$$\begin{aligned} L_{zs} &= 0, \quad \phi_s = \frac{\hbar g_\phi c_s^* c_s}{I\omega_\phi^2}, \\ p_s &= 0, \quad q_s = \frac{\hbar g_z c_s^* c_s}{m\omega_z^2}, \\ a_s &= -\frac{ig\sqrt{N}}{\gamma_a + i\Delta_a} c_s, \\ c_s &= \frac{\varepsilon_l(\gamma_a + i\Delta_a)}{(\kappa + i\Delta)(\gamma_a + i\Delta_a) + g^2 N}, \end{aligned} \quad (3)$$

其中, $\Delta = \Delta_c - g_\phi \phi_s - g_z q_s$ 表示腔模与泵浦场之间的有效失谐. 由于腔场 c 的稳态值 c_s 远大于涨落项 δc , 因此在求解式(1)时忽略二阶非线性涨落项 $\delta c^\dagger \delta c$, $\delta q \delta c$ 和 $\delta \phi \delta c$, 保留线性项和一阶涨落项, 从而得到线性化的海森堡-朗之万方程:

$$\begin{aligned} \delta \dot{\phi} &= \frac{\delta L_z}{I}, \\ \delta \dot{L}_z &= \hbar g_\phi (c_s^* \delta c + c_s \delta c^\dagger) - I\omega_\phi^2 \delta \phi - \gamma_\phi \delta L_z, \\ \delta \dot{q} &= \frac{\delta p}{m}, \\ \delta \dot{p} &= \hbar g_z (c_s^* \delta c + c_s \delta c^\dagger) - m\omega_z^2 \delta q - \gamma_z \delta p, \\ \delta \dot{c} &= ig_\phi (\phi_s \delta c + c_s \delta \phi) - (\kappa + i\Delta_c) \delta c \\ &\quad + ig_z (q_s \delta c + c_s \delta q) + \varepsilon_p e^{-i\Delta_p t} - ig \delta a \sqrt{N}, \\ \delta \dot{a} &= -(\gamma_a + i\Delta_a) \delta a - ig \delta c \sqrt{N}. \end{aligned} \quad (4)$$

在弱探测场条件下, 只考虑系统产生与探测频率 ω_p 相关的一阶边带, 忽略高阶边带, 因此将涨落项 δA 拆分为

$$\delta A = A_+ \varepsilon_p e^{-i\Delta_p t} + A_- \varepsilon_p^* e^{i\Delta_p t}, \quad (5)$$

式中 A_+ , A_- 是与场振幅 ε_p 无关的复数响应系数. 对厄米算符的涨落项(如 δq , δp , $\delta \phi$, δL_z), 满足 $\delta A^\dagger = \delta A$, 其正负频率系数互为共轭 $A_+ = A_-^*$; 对于非厄米算符的涨落项(如 δc , δa), 满足 $\delta A^\dagger = (\delta A)^\dagger$, 其正负频率系数 A_+ 和 A_- 相互独立. 将式(5)代入式(4)得到各涨落项对探测场的响应系数分别为

$$\begin{aligned}\phi_+ &= \frac{\hbar g_\phi (c_s^* c_+ + c_s c_-^*)}{I(\omega_\phi^2 - \Delta_p^2 - i\Delta_p \gamma_\phi)}, \quad \phi_- = \frac{\hbar g_\phi (c_s^* c_- + c_s c_+^*)}{I(\omega_\phi^2 - \Delta_p^2 + i\Delta_p \gamma_\phi)}, \quad q_+ = \frac{\hbar g_z (c_s^* c_+ + c_s c_-^*)}{m(\omega_z^2 - \Delta_p^2 - i\Delta_p \gamma_z)}, \quad q_- = \frac{\hbar g_z (c_s^* c_- + c_s c_+^*)}{m(\omega_z^2 - \Delta_p^2 + i\Delta_p \gamma_z)}, \\ c_+ &= \frac{[ic_s(g_\phi \phi_+ + g_z q_+) + 1](\gamma_a - i\Delta_p + i\Delta_a)}{[\kappa + i(\Delta - \Delta_p)](\gamma_a - i\Delta_p + i\Delta_a) + g^2 N}, \quad c_- = \frac{ic_s(g_\phi \phi_- + g_z q_-)(\gamma_a + i\Delta_p + i\Delta_a)}{[\kappa + i(\Delta + \Delta_p)](\gamma_a + i\Delta_p + i\Delta_a) + g^2 N}.\end{aligned}\quad (6)$$

联立式(3)和(6)求得

$$c_+ = \frac{(\gamma_a - i\Delta_p + i\Delta_a)(1 - M)}{[\kappa + i(\Delta - \Delta_p)](\gamma_a - i\Delta_p + i\Delta_a)(1 - M) + g^2 N(1 - M) + MG^*(\gamma_a - i\Delta_p + i\Delta_a)}, \quad (7)$$

其中

$$\begin{aligned}M &= -i |c_s|^2 [\hbar g_\phi^2 / I(\omega_\phi^2 - \Delta_p^2 - i\Delta_p \gamma_\phi) \\ &\quad + \hbar g_z^2 / m(\omega_z^2 - \Delta_p^2 - i\Delta_p \gamma_z)] / G_-^*, \\ G_-^* &= \kappa - i(\Delta + \Delta_p) + g^2 N / (\gamma_a - i\Delta_p - i\Delta_a).\end{aligned}$$

假设左右腔镜具有相同的耦合衰减率, 根据腔场的标准输入-输出关系^[60]可以得到

$$\begin{aligned}\varepsilon_T^{\text{out}}(t) &= \langle c \rangle \sqrt{2\kappa_{\text{ex}}}, \\ \varepsilon_R^{\text{out}}(t) + \varepsilon_l^{\text{in}} + \varepsilon_p^{\text{in}} e^{-i\Delta t} &= \langle c \rangle \sqrt{2\kappa_{\text{ex}}}.\end{aligned}\quad (8)$$

为明确输出场中不同频率分量的贡献, 将左侧透射输出场 $\varepsilon_T^{\text{out}}$ 和右侧反射输出场 $\varepsilon_R^{\text{out}}$ 分别展开为

$$\begin{aligned}\varepsilon_T^{\text{out}}(t) &= \varepsilon_{T(s)}^{\text{out}} + \varepsilon_{T\varepsilon_p}^{\text{in}} e^{-i\Delta t} + \varepsilon_{T\varepsilon_p}^{\text{in}*} e^{i\Delta t}, \\ \varepsilon_R^{\text{out}}(t) &= \varepsilon_{R(s)}^{\text{out}} + \varepsilon_{R\varepsilon_p}^{\text{in}} e^{-i\Delta t} + \varepsilon_{R\varepsilon_p}^{\text{in}*} e^{i\Delta t},\end{aligned}\quad (9)$$

其中 $\varepsilon_{T(s)}^{\text{out}}$ 和 $\varepsilon_{R(s)}^{\text{out}}$ 对应频率为 ω_l 的透射和反射输出场, $\varepsilon_{T\varepsilon_p}^{\text{in}} e^{-i\Delta t}$ 和 $\varepsilon_{R\varepsilon_p}^{\text{in}} e^{-i\Delta t}$ 对应频率 ω_p 的透射和反射输出场, $\varepsilon_{T\varepsilon_p}^{\text{in}*} e^{i\Delta t}$ 和 $\varepsilon_{R\varepsilon_p}^{\text{in}*} e^{i\Delta t}$ 对应频率 ω_p 的透射和反射输出场的共轭项, 其实部描述输出场的吸收性质, 虚部描述输出场的色散性质, 而共轭项 $\varepsilon_{T\varepsilon_p}^{\text{in}*} e^{i\Delta t}$ 和 $\varepsilon_{R\varepsilon_p}^{\text{in}*} e^{i\Delta t}$ 对应

由非线性四波混频过程产生的频率为 $2\omega_l - \omega_p$ 的场. 将

腔场 $c = c_s + c_+ \varepsilon_p e^{-i\Delta t} + c_- \varepsilon_p^* e^{i\Delta t}$ 和泵浦(探测)场

$\varepsilon_l = \varepsilon_l^{\text{in}} \sqrt{2\kappa_{\text{ex}}} (\varepsilon_p = \varepsilon_p^{\text{in}} \sqrt{2\kappa_{\text{ex}}})$ 代入式(8), 通过比较式(8)和(9)对应频率分量的系数, 可以得到

$$\begin{aligned}\varepsilon_{T(s)}^{\text{out}} &= c_s \sqrt{2\kappa_{\text{ex}}}, \quad \varepsilon_{R(s)}^{\text{out}} = (c_s - \varepsilon_l) \sqrt{2\kappa_{\text{ex}}}, \\ \varepsilon_T &= 2\kappa_{\text{ex}} c_+, \quad \varepsilon_R = 2\kappa_{\text{ex}} c_- - 1.\end{aligned}\quad (10)$$

由式(10)可以得到系统透射率和反射率^[61]分别为

$$\begin{aligned}T &= |2\kappa_{\text{ex}} c_+|^2, \\ R &= |2\kappa_{\text{ex}} c_- - 1|^2.\end{aligned}\quad (11)$$

式(10)表明探测场的透射和反射振幅 ε_R 和 ε_T 只相差一个常数项1, 二者的物理特性具有一致性, 因此本文将重点围绕 ε_T 开展讨论.

3 结果和讨论

为了对系统的稳态光力学响应特性进行研究, 首先需要对系统进行稳定性分析. 为此将式(4)进一步改写为

$$\dot{u}(t) = Mu(t),$$

$$M = \begin{pmatrix} 0 & \frac{1}{I} & 0 & 0 & 0 & 0 & 0 & 0 \\ -I\omega_\phi^2 & -\gamma_\phi & 0 & 0 & \sqrt{2}\hbar g_\phi a_r & \sqrt{2}\hbar g_\phi a_i & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{m} & 0 & 0 & 0 & 0 \\ 0 & 0 & -m\omega_z^2 & -\gamma_z & \sqrt{2}\hbar g_z a_r & \sqrt{2}\hbar g_z a_i & 0 & 0 \\ -\sqrt{2}\hbar g_\phi a_i & 0 & -\sqrt{2}\hbar g_z a_i & 0 & -\kappa & \Delta & 0 & g\sqrt{N} \\ \sqrt{2}\hbar g_\phi a_r & 0 & \sqrt{2}\hbar g_z a_r & 0 & -\Delta & -\kappa & -g\sqrt{N} & 0 \\ 0 & 0 & 0 & 0 & 0 & g\sqrt{N} & -\gamma_a & \Delta_a \\ 0 & 0 & 0 & 0 & -g\sqrt{N} & 0 & \Delta_a & -\gamma_a \end{pmatrix}, \quad (12)$$

其中 $u(t) = (\delta\phi, \delta L_z, \delta q, \delta p, \delta X, \delta Y, \delta U, \delta V)^T$, $X = (\delta c + \delta c^\dagger) / \sqrt{2}$, $Y = (\delta c - \delta c^\dagger) / \sqrt{2}i$, $U = (\delta a + \delta a^\dagger) / \sqrt{2}$, $V = (\delta a - \delta a^\dagger) / \sqrt{2}i$, $a_r = \text{Re}[c_s]$, $a_i = \text{Im}[c_s]$. 只有矩阵 M 的特征值的实部均为负值时^[62], 系统各算符平均值才能够在相空间中趋于一个稳定值, 该稳定性条件也可以通过Routh-Hurwitz准则^[63]进行判定, 但是其形式非常复杂. 我们通过直接数值求解 M 矩阵本征值的方法来保证所使用的系统参数均满足解的稳定性条件. 在没有特殊说明情况下, 系统参数取值如下: $L=1$ mm, $m=10$ ng, $r=16$ μm , $\gamma_z/2\pi=\gamma_\phi/2\pi=700$ Hz, $\gamma_z/2\pi=2.875$ MHz, $\omega_z/2\pi=10$ MHz, $\omega_\phi/2\pi=8$ MHz, $\omega_l/2\pi=3700$ THz, 对应泵浦场波长 $\lambda_l=810$ nm, $\eta_c=0.5$. 本文提出的嵌入二能级原子系综的拉盖尔-高斯旋振腔光力学系统可基于当前的冷原子与微腔耦合实验平台实现^[64]. 通过微纳加工技术可制备高质量的旋振腔^[65], 利用磁光阱技术俘获和冷却⁸⁷Rb原子系综^[66], 将原子系综装载至高精细度的L-G腔中, 实现腔场、原子系综与旋振镜之间的耦合^[67]. 文中选取的原子弛豫速率 $\gamma_a/2\pi=2.875$ MHz取自⁸⁷Rb原子D₁线 $|5S_{1/2}\rangle \rightarrow |5P_{1/2}\rangle$ 跃迁的实验测量值^[68]; 微腔尺寸、腔场衰减率、旋振镜质量与尺寸、振频率等参数均处于当前实验技术可实现范围内, 具有良好的实验可行性^[18,64,69–72].

在不同耦合机制下, 系统输出探测场具有完全不同的吸收和色散性质. 图2(a)是不存在泵浦场和原子系综情况下的探测场输出, 其吸收谱呈现出标准的洛伦兹线型, 表明探测场被腔共振吸收. 当仅存在泵浦场激发, 而腔内无原子系综时, 如图2(b)所示, $P_l=1$ mW, $g\sqrt{N}=0$, 此时腔场与旋振镜之间的光旋转耦合和光辐射压耦合主导系统的动力学过程, 泵浦场与旋振镜之间发生非线性相互作用, 生成了斯托克斯光子($\omega_l-\omega_z$, $\omega_l-\omega_\phi$)或反斯托克斯光子($\omega_l+\omega_z$, $\omega_l+\omega_\phi$). 当满足边带跃迁条件(ω_z , $\omega_\phi > \kappa$)时, 斯托克斯场因远离腔模共振而被强烈抑制; 在吸收谱中 $\Delta_p=\omega_\phi$ 和 $\Delta_p=\omega_z$ 处, 探测场与反斯托克斯场之间频率相同且相位相差 π 而发生相消干涉, 因此可以观察到两个清晰的 OMIT 窗口. 图2(c)展示了 $P_l=0$, $g\sqrt{N}/2\pi=3.8$ MHz 的情况, 此时只存在腔场与原子系综之间的耦合, 在共振频率处出现一个 EIT 窗口, 这源于原子两条激发路径之间的干涉: 探测场对原子的直接激发以及腔场通过与原子

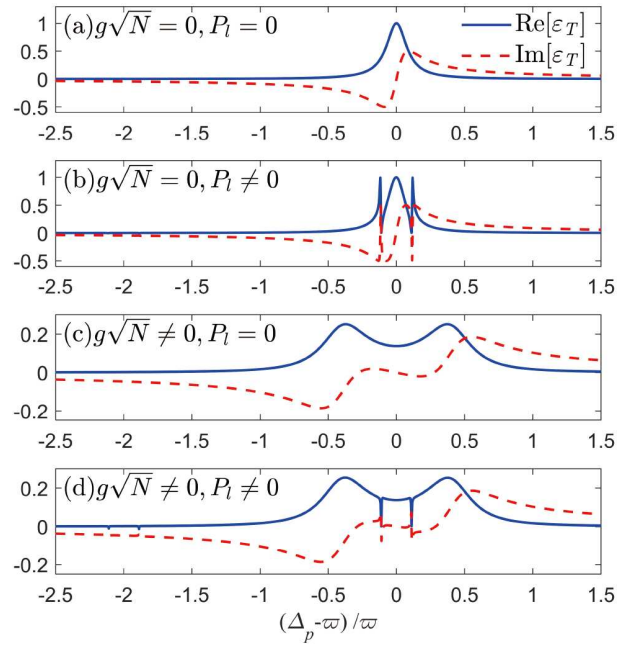


图 2 (网络版彩图)不同耦合机制下, 输出探测场的吸收性质 $\text{Re}[\varepsilon_T]$ (蓝色实线) 和色散性质 $\text{Im}[\varepsilon_T]$ (红色虚线) 随着归一化失谐 $(\Delta_p - \omega)/\omega$ 演化. (a) $P_l=0$, $g\sqrt{N}/2\pi=0$; (b) $P_l=1$ mW, $g\sqrt{N}/2\pi=0$; (c) $P_l=0$, $g\sqrt{N}/2\pi=3.8$ MHz; (d) $P_l=1$ mW, $g\sqrt{N}/2\pi=3.8$ MHz. 其中 $\Delta_a=\omega$, $\Delta=\omega$, $\kappa/2\pi=0.8$ MHz, $l=72$, $\omega=(\omega_z+\omega_\phi)/2$.

Figure 2 (Color online) Absorption property $\text{Re}[\varepsilon_T]$ (blue solid line) and dispersion property $\text{Im}[\varepsilon_T]$ (red dashed line) of the probe field output as a function of the normalized detuning $(\Delta_p - \omega)/\omega$ under different coupling mechanisms. (a) $P_l=0$, $g\sqrt{N}/2\pi=0$; (b) $P_l=1$ mW, $g\sqrt{N}/2\pi=0$; (c) $P_l=0$, $g\sqrt{N}/2\pi=3.8$ MHz; (d) $P_l=1$ mW, $g\sqrt{N}/2\pi=3.8$ MHz. $\Delta_a=\omega$, $\Delta=\omega$, $\kappa/2\pi=0.8$ MHz, $l=72$, $\omega=(\omega_z+\omega_\phi)/2$.

系综之间的耦合激发原子. 当两条路径的跃迁幅度相等且相位相反时, 发生相消干涉, 导致原本共振吸收的探测场不被原子吸收, 从而形成一个标准的 EIT 透明窗口. 同时由于原子弛豫速率较大, EIT 窗口表现出较宽且较浅的特征. 在图 2(d) 中, $P_l=1$ mW, $g\sqrt{N}/2\pi=3.8$ MHz, 系统中存在腔场与旋振镜之间的光辐射压耦合、光旋转耦合以及腔场与二能级原子之间的耦合. 此时在共振频率附近, 可观察到由两个 OMIT 窗口与一个 EIT 窗口共同构成的混合窗口. 原子的存在增大了腔场与旋振镜之间的相互作用, 同时原子作为非线性媒介, 为不同频率光场的能量转换提供通道, 使更多的泵浦场光子与旋振镜发生非线性相互作用, 产生斯托克斯光子. 在吸收谱中 $\Delta_p=-\omega_\phi$, $\Delta_p=-\omega_z$ 处的探测场与斯托克斯场发生相长干涉, 形成吸收增益.

图3展示了原子系综集体耦合强度对探测场输出的影响. 假设原子与腔模之间的耦合系数 g 不变, 通过改变原子数目 N 来调控集体耦合强度 $g\sqrt{N}$. 从图3(a)中可以看到, 当腔场与原子系综的集体耦合强度处于弱耦合 $g\sqrt{N} < (\kappa + \gamma_a)/2$ 时, 随着原子数目的增加, 吸收峰峰值强度逐渐降低. 此时, 原子系综与腔场之间的耦合强度不足以克服腔场衰减和原子弛豫的影响, 激发原子两条路径之间的相消干涉较弱, 腔场与原子之间的耦合可以忽略. 当腔场与原子系综之间的耦合进入强耦合区域 $g\sqrt{N} > (\kappa + \gamma_a)/2$ 时, 吸收谱中出现一个EIT窗口, 吸收峰值随着耦合强度增大而减弱, 且EIT窗口的宽度和深度均增加. 为进一步研究强耦合条件下, 集体耦合强度 $g\sqrt{N}$ 对吸收谱的影响, 图3(c)绘制了左侧吸收峰峰值与右侧吸收峰峰值之间的间距 d_1

随 $g\sqrt{N}$ 变化的函数图像. 结果表明, 左侧和右侧吸收峰峰值之间的位置间距 d_1 与集体耦合强度 $g\sqrt{N}$ 呈现线性关系, 且随着集体耦合强度的增大而增加, 因此通过测量左右两侧吸收峰的间距可以确定原子系综与腔场的耦合强度. 在强耦合条件下, 随着原子系综与腔场之间的集体耦合强度的增加, 以原子为媒介的非线性过程增强, 使得斯托克斯光子和反斯托克斯光子数目增多, 导致OMIT透明窗口深度和宽度增加, 吸收增益增强.

图4给出了不同拓扑荷数 l 情况下, 探测场吸收随着归一化失谐的变化. 结果表明, 当拓扑荷数 $l=0$ 时, 不存在与转动模式对应的OMIT窗口及吸收增益; 随着拓扑荷数 l 增大, 吸收谱中出现与转动模式相关的OMIT窗口, 并在 $\Delta_p = -\omega_\phi$ 处出现吸收增益现象, 该现象说明反斯托克斯光子和斯托克斯光子的产生与腔场

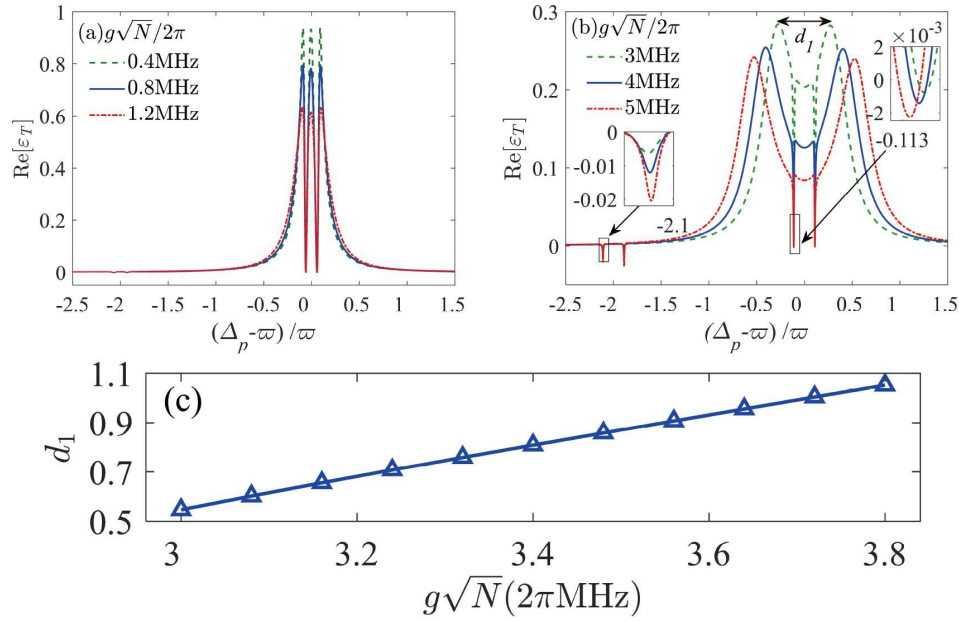


图3 (网络版彩图)不同原子系综集体耦合强度对探测场输出的影响. (a) 在弱集体耦合条件下, 不同 $g\sqrt{N}$ 取值对应的输出探测场的吸收性质 $\text{Re}[\varepsilon_T]$ 随着归一化失谐 $(\Delta_p - \omega)/\omega$ 演化情况. 其中 $g\sqrt{N}/2\pi = 0.4$ MHz(绿色虚线), $g\sqrt{N}/2\pi = 0.8$ MHz(蓝色实线), $g\sqrt{N}/2\pi = 1.2$ MHz(红色点划线). (b) 在强集体耦合条件下, 不同 $g\sqrt{N}$ 取值对应的输出探测场的吸收性质 $\text{Re}[\varepsilon_T]$ 随着归一化失谐 $(\Delta_p - \omega)/\omega$ 演化情况. 其中 $g\sqrt{N}/2\pi = 3$ MHz(绿色虚线), $g\sqrt{N}/2\pi = 4$ MHz(蓝色实线), $g\sqrt{N}/2\pi = 5$ MHz(红色点划线). (c) 在强集体耦合条件下, 输出探测场的吸收谱左侧峰值与右侧峰值之间的间距 d_1 随着 $g\sqrt{N}$ 的变化. $\Delta_a = \omega$, $\Delta = \omega$, $\kappa/2\pi = 0.8$ MHz, $P_l = 2$ mW, $l = 72$, $\omega = (\omega_z + \omega_\phi)/2$

Figure 3 (Color online) The influence of the collective coupling strength of the atomic ensemble on the output of the probe field. (a) Absorption property $\text{Re}[\varepsilon_T]$ of the probe field output as a function of the normalized detuning $(\Delta_p - \omega)/\omega$ for different $g\sqrt{N}$ values under weak collective couplings: $g\sqrt{N}/2\pi = 0.4$ MHz (green dashed line), $g\sqrt{N}/2\pi = 0.8$ MHz (blue solid line), $g\sqrt{N}/2\pi = 1.2$ MHz (red dash dotted line); (b) absorption property $\text{Re}[\varepsilon_T]$ of the probe field output as a function of the normalized detuning $(\Delta_p - \omega)/\omega$ for different $g\sqrt{N}$ values under strong collective couplings: $g\sqrt{N}/2\pi = 3$ MHz (green dashed line), $g\sqrt{N}/2\pi = 4$ MHz (blue solid line), $g\sqrt{N}/2\pi = 5$ MHz (red dash dotted line); (c) dependence of the spacing d_1 between the left and right absorption peaks on $g\sqrt{N}$ in the strong coupling regime. $\Delta_a = \omega$, $\Delta = \omega$, $\kappa/2\pi = 0.8$ MHz, $P_l = 2$ mW, $l = 72$, $\omega = (\omega_z + \omega_\phi)/2$.

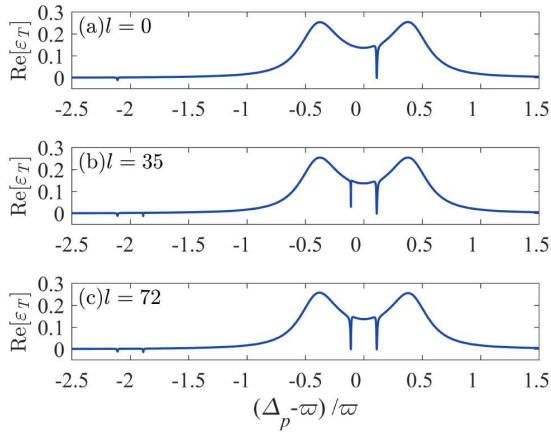


图 4 (网络版彩图)不同拓扑荷数取值情况下, 探测场的吸收性质 $\text{Re}[\varepsilon_T]$ 随着归一化失谐 $(\Delta_p - \omega)/\omega$ 演化情况. (a) $l=0$; (b) $l=35$; (c) $l=72$. $\Delta_a = \omega$, $\Delta = \omega$, $\kappa/2\pi = 0.8$ MHz, $P_l = 2$ mW, $g\sqrt{N}/2\pi = 3.8$ MHz, $\omega = (\omega_z + \omega_\phi)/2$.

和旋振镜之间的耦合强度密切相关. 同时, 转动模式对应的 OMIT 窗口深度和宽度均随 l 的增大而增加, 而振动模式相关的透明窗口并未有明显变化. 这一现象源于拓扑荷数 l 对光旋转耦合强度 $g_\phi = cl/L$ 的调控作用, 增大拓扑荷数直接增强了腔场与转动模式之间的耦合强度, 使得斯托克斯过程和反斯托克斯过程增强, 从而加深了转动相关的 OMIT 窗口, 同时增强了对应的吸收增益响应. 而辐射压力耦合强度 g_z 主要由腔模与振动模式的耦合特性决定, 与拓扑荷数 l 无直接关联, 因此拓扑荷数变化不会显著影响振动模式对应的 OMIT 窗口和吸收增益.

图 5 中我们讨论腔场衰减率对系统探测场吸收性质的影响. 由于腔场的存在会改变 OMIT 两条干涉路径之间的相位匹配条件, 而腔场衰减的增大使得探测场和反斯托克斯场更加接近理想的干涉相消条件, 因此 OMIT 窗口的深度变深. EIT 依赖原子系综与腔之间的耦合强度, 腔场衰减率增大导致腔内光子数减少, 使得腔场激发原子路径削弱显著, 导致 EIT 窗口深度变浅. 腔场衰减率增大, 引起吸收谱线展宽, 使得 OMIT 窗口变宽, 同时增强了腔模对斯托克斯场的响应, 使得吸收增益增强.

泵浦场功率对探测场输出也有一定的调制作用. 从图 6(a) 可以看到, 随着泵浦场功率从 $P_l = 1$ mW 增加到

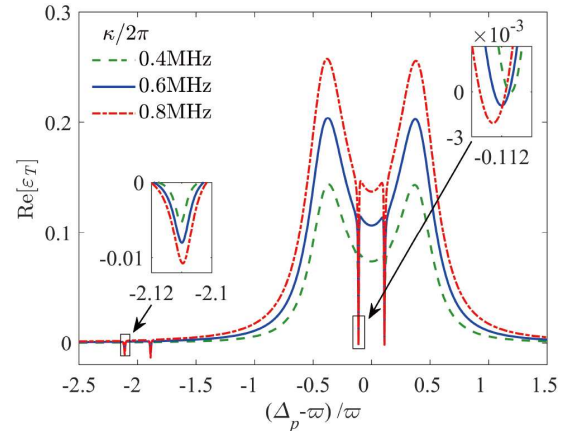


图 5 (网络版彩图)不同腔场衰减率取值情况下, 输出探测场的吸收性质 $\text{Re}[\varepsilon_T]$ 随着归一化失谐 $(\Delta_p - \omega)/\omega$ 演化情况. 腔场衰减率分别为 $\kappa/2\pi = 0.4$ MHz (绿色虚线), $\kappa/2\pi = 0.6$ MHz (蓝色实线), $\kappa/2\pi = 0.8$ MHz (红色点划线). $\Delta_a = \omega$, $\Delta = \omega$, $g\sqrt{N}/2\pi = 3.8$ MHz, $P_l = 2$ mW, $l = 72$, $\omega = (\omega_z + \omega_\phi)/2$.

$P_l = 5$ mW, 吸收谱左右两侧吸收峰值变大, 两个 OMIT 透明窗口变宽, 中心峰逐渐变窄, 左右两侧吸收峰峰值间距 d_2 与泵浦场功率成正比关系 (图 6(b)). 泵浦场功率的增大使得腔内光子数增多, 导致腔场与旋振镜之间光辐射压耦合和光旋转耦合增强, 进而使得 OMIT 窗口宽度增加.

图 7 通过调节腔模与泵浦场之间的失谐 Δ 以及原子系综与泵浦场之间的失谐 Δ_a , 可以改变吸收谱线的线型和分布. 在图 7(a) 和 (b) 中, 当 $\Delta_a = \Delta = \omega - g\sqrt{N}$ ($\Delta_a = \Delta = \omega + g\sqrt{N}$) 时, 探测场和反斯托克斯场两条干涉路径之间相对相位的变化, 使得吸收谱出现不对称的法诺共振线型. 同时, 原子共振激发的频率发生改变, 导致在吸收谱中 EIT 透明窗口的中心位置从 $\Delta_p = \omega$ 处向左 (右) 移动. 该现象表明可以通过协同调控原子系综与泵浦场之间的失谐以及腔模与泵浦场之间的有效失谐大小, 实现 EIT 窗口位置的精确调控. 在图 7(c) 和 (d) 中, 保持腔模与泵浦场之间的有效失谐 $\Delta = \omega$ 不变, 仅改变原子系综与泵浦场之间的失谐大小 $\Delta_a = \omega - g\sqrt{N}$ 时, EIT 窗口向左移动, 同时 EIT 形成的两条路径之间的相位发生变化, 导致左侧吸收峰

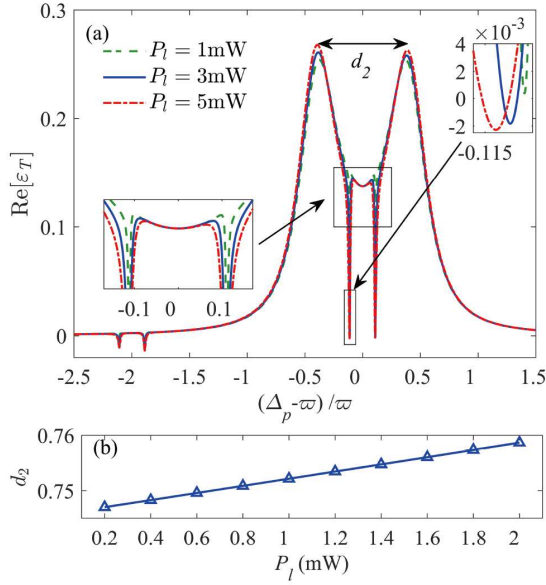


图 6 (网络版彩图) 泵浦场功率对探测场输出的影响. (a) 不同泵浦场功率取值情况下, 输出探测场的吸收性质 $\text{Re}[\varepsilon_T]$ 随着归一化失谐 $(\Delta_p - \omega)/\omega$ 演化情况. $P_l = 1$ mW (绿色虚线), $P_l = 3$ mW (蓝色实线), $P_l = 5$ mW (红色点划线). (b) 输出探测场吸收谱左右两侧吸收峰峰值之间的距离 d_2 随着泵浦场功率的变化. $\Delta_a = \omega$, $\Delta = \omega$, $\kappa/2\pi = 0.8$ MHz, $g\sqrt{N}/2\pi = 3.8$ MHz, $l = 72$, $\sigma = (\omega_z + \omega_\phi)/2$

Figure 6 (Color online) Dependence of the probe field output on the pump field power. (a) Absorption property $\text{Re}[\varepsilon_T]$ of the output as a function of the normalized detuning $(\Delta_p - \omega)/\omega$. $P_l = 1$ mW (green dashed line), $P_l = 3$ mW (blue solid line), $P_l = 5$ mW (red dash-dotted line). (b) The distance d_2 between the left and right absorption peaks as a function of the pump field power. $\Delta_a = \omega$, $\Delta = \omega$, $\kappa/2\pi = 0.8$ MHz, $g\sqrt{N}/2\pi = 3.8$ MHz, $l = 72$, $\sigma = (\omega_z + \omega_\phi)/2$.

减弱而右侧吸收峰显著增强, 因此在吸收谱中出现不对称的法诺共振线型; 当 $\Delta_a = \omega + g\sqrt{N}$ 时, 吸收谱的变化趋势与图 7(c) 所示情况相反. 在图 7(e) 和 (f) 中保持原子失谐不变, 仅改变腔模有效失谐 $\Delta = \omega - g\sqrt{N}$ 时, 改变了探测场和反斯托克斯场之间的干涉相位, 以及 EIT 形成的两条路径之间的相位, 在吸收谱中 EIT 窗口的两个吸收峰合并为一个, 且左侧吸收峰增强, 出现不对称法诺共振线型; 而当 $\Delta = \omega + g\sqrt{N}$ 时, 右侧吸收峰则会增强. 上述现象共同揭示了原子系综与泵浦场之间失谐、腔模与泵浦场之间的有效失谐变化, 能够改变腔内不同耦合路径与探测场之间的干涉叠加, 从而影响系统的吸收性质.

图 8 是不同失谐条件下, 探测场的透射率 T 和反射率 R 变化曲线. 从图中我们可以看到在 $\Delta_p = \omega_\phi$, $\Delta_p = \omega_z$ 处, 不存在透射光只存在反射光, 即系统左侧有光输

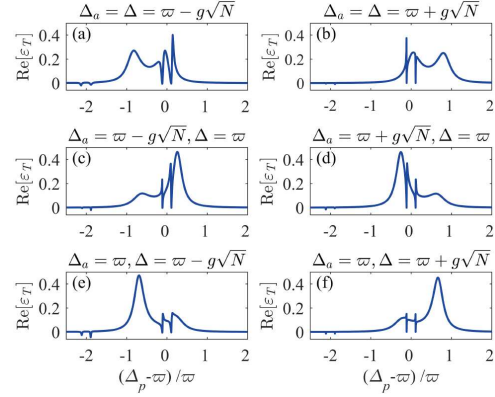


图 7 (网络版彩图) 原子系综与泵浦场失谐 Δ_a 以及腔模与泵浦场有效失谐 Δ 对探测场输出 $\text{Re}[\varepsilon_T]$ 的影响. (a) $\Delta_a = \Delta = \omega - g\sqrt{N}$; (b) $\Delta_a = \Delta = \omega + g\sqrt{N}$; (c) $\Delta_a = \omega - g\sqrt{N}$, $\Delta = \omega$; (d) $\Delta_a = \omega + g\sqrt{N}$, $\Delta = \omega$; (e) $\Delta_a = \omega$, $\Delta = \omega - g\sqrt{N}$; (f) $\Delta_a = \omega$, $\Delta = \omega + g\sqrt{N}$. $\kappa/2\pi = 0.8$ MHz, $g\sqrt{N}/2\pi = 3.8$ MHz, $P_l = 2$ mW, $l = 72$, $\sigma = (\omega_z + \omega_\phi)/2$

Figure 7 (Color online) Dependence of the absorption property $\text{Re}[\varepsilon_T]$ of the probe field output on the detuning Δ_a between the atomic ensemble and the pump field, and the effective detuning Δ between the cavity mode and the pump field. (a) $\Delta_a = \Delta = \omega - g\sqrt{N}$; (b) $\Delta_a = \Delta = \omega + g\sqrt{N}$; (c) $\Delta_a = \omega - g\sqrt{N}$, $\Delta = \omega$; (d) $\Delta_a = \omega + g\sqrt{N}$, $\Delta = \omega$; (e) $\Delta_a = \omega$, $\Delta = \omega - g\sqrt{N}$; (f) $\Delta_a = \omega$, $\Delta = \omega + g\sqrt{N}$. $\kappa/2\pi = 0.8$ MHz, $g\sqrt{N}/2\pi = 3.8$ MHz, $P_l = 2$ mW, $l = 72$, $\sigma = (\omega_z + \omega_\phi)/2$.

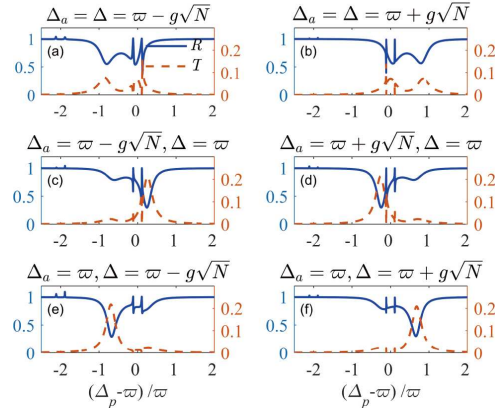


图 8 (网络版彩图) 不同原子系综与泵浦场失谐、腔模与泵浦场有效失谐条件下, 探测场的反射率 R (蓝色实线) 和透射率 T (红色虚线) 随着归一化失谐 $(\Delta_p - \omega)/\omega$ 演化情况. (a) $\Delta_a = \Delta = \omega - g\sqrt{N}$; (b) $\Delta_a = \Delta = \omega + g\sqrt{N}$; (c) $\Delta_a = \omega - g\sqrt{N}$, $\Delta = \omega$; (d) $\Delta_a = \omega + g\sqrt{N}$, $\Delta = \omega$; (e) $\Delta_a = \omega$, $\Delta = \omega - g\sqrt{N}$; (f) $\Delta_a = \omega$, $\Delta = \omega + g\sqrt{N}$. Where $\kappa/2\pi = 0.8$ MHz, $g\sqrt{N}/2\pi = 3.8$ MHz, $P_l = 2$ mW, $l = 72$, $\sigma = (\omega_z + \omega_\phi)/2$

Figure 8 (Color online) The reflection spectrum R (blue solid line) and transmission spectrum T (red dashed line) of the probe field output as a function of the normalized detuning $(\Delta_p - \omega)/\omega$ with different detunings between the atomic ensemble and the pump field, and different effective detunings between the cavity mode and pump field. (a) $\Delta_a = \Delta = \omega - g\sqrt{N}$; (b) $\Delta_a = \Delta = \omega + g\sqrt{N}$; (c) $\Delta_a = \omega - g\sqrt{N}$, $\Delta = \omega$; (d) $\Delta_a = \omega + g\sqrt{N}$, $\Delta = \omega$; (e) $\Delta_a = \omega$, $\Delta = \omega - g\sqrt{N}$; (f) $\Delta_a = \omega$, $\Delta = \omega + g\sqrt{N}$. Where $\kappa/2\pi = 0.8$ MHz, $g\sqrt{N}/2\pi = 3.8$ MHz, $P_l = 2$ mW, $l = 72$, $\sigma = (\omega_z + \omega_\phi)/2$.

出, 系统右侧无光输出, 因此系统可以在 $\Delta_p=\omega_\phi$, $\Delta_p=\omega_z$ 处实现探测场的单向输出. 通过改变原子系综与泵浦场之间的失谐以及腔模与泵浦场之间的有效失谐大小, 可灵活调控能量在透射、反射和吸收之间的分配, 进一步说明原子系综与泵浦场之间的失谐、腔模与泵浦场的有效失谐会对探测场吸收性质产生影响. 在特定频率处反射率大于1, 这是因为腔场以原子为媒介将能量转移至探测场, 从而产生增益现象.

4 结论

本文主要研究了嵌入二能级原子系综的L-G旋振腔系统的输出探测场特性. 系统中同时存在腔场与旋振镜的光旋转耦合、光辐射压耦合以及原子系综与腔场的耦合, 使得在吸收谱中可同时观测到EIT窗口和双OMIT窗口. 研究发现, 调节原子系综与腔集体耦合强度可改变EIT窗口的深度与宽度, 此外通过测量吸收谱

中左右两侧吸收峰之间的间距, 可精确测量原子系综与腔场之间的耦合强度; 改变泵浦场功率可有效调控OMIT窗口的宽度和深度; 调控腔模拓扑荷数可改变腔场与旋振镜的光旋转耦合强度, 进而改变转动模式相关的OMIT窗口深度和宽度; 腔场衰减率主要影响EIT窗口对应的干涉路径, 从而影响系统吸收性质. 此外, 通过调节原子系综与泵浦失谐以及腔模与泵浦场的有效失谐, 可以使得吸收谱出现多重不对称法诺共振, 实现对输出场能量在透射、反射与吸收通道的分配调控. 同时, 原子的存在会导致吸收谱在特定频率处出现吸收增益, 且增益随着原子数目和腔场衰减率的增加而增强. 本文提出的基于光学微腔与原子系综耦合的EIT-OMIT协同调控机制, 克服了传统单一透明效应调控自由度少、工作频带窄的局限, 为量子存储器件提升存储带宽和模式兼容性以及为光开关器件提升开关对比度和多通道独立调控能力, 提供了理论参考和参数优化方向.

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Atomic-ensemble-mediated modulation of optomechanical properties in a Laguerre-Gaussian rovibrational cavity

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Cavity optomechanics serves not only as a crucial platform for exploring novel quantum phenomena but also as a technological engine for next-generation precision measurement, quantum information technologies, and the development of new functional devices. In this paper, by solving the Heisenberg-Langevin equations, we investigate the optomechanical properties of a Laguerre-Gaussian (L-G) rovibrational cavity system embedded with an atomic ensemble. It is found that due to the coupling of the cavity field with both the atomic ensemble and the rovibrational mirror, the absorption spectrum of the probe field exhibits coexisting double optomechanically induced transparency (OMIT) and electromagnetically induced transparency (EIT) windows. Furthermore, the coupling between the atomic ensemble and the cavity field gives rise to absorption gain phenomena. By adjusting the number of atoms in the ensemble and the power of the pump field, the depth and width of the EIT and OMIT windows can be controlled. The peak intensity of the absorption spectrum can be controlled by adjusting the cavity decay rate; the depth and width of the OMIT window associated with the rotational mode can be manipulated by changing the topological charge of the cavity mode. By tuning the effective detuning between the cavity mode and the pump field, as well as the detuning between the atomic ensemble and the pump field, the absorption spectrum can exhibit asymmetric multiple Fano resonances, thereby enabling flexible control of the output field energy distribution among transmission, reflection, and absorption channels.

Laguerre-Gaussian rovibrational cavity, atomic ensemble, electromagnetically induced transparency, optomechanically induced transparency, Fano resonance

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