第13卷 第1期　　光　学　学　报　　Vol. 13, No. 1
1993年1月　　ACTA OPTICA SINICA　　January, 1993

在V型系统中原子相干对吸收-色散关系的影响

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提　　要

在V型能级系统原子介质中，若利用外场产生相干，则弱光场在该介质中的吸收-色散关系将展现出新的特性. 特别是当弱场具有某一特定频率时，介质对光的吸收为零但光折射率大于1.

关键词　原子相干，　吸收-色散关系.

利用量子干涉效应，Scully[1,2] 首次阐明了制备一种光在其中不被吸收、但可获得大折射率的新型光学材料的可能性. 光在介质中存在零吸收和大折射率的现象可望在光学显微镜[3]、探测弱相互作用中，宇称破缺的实验[4]等方面获得应用，具有重要意义.

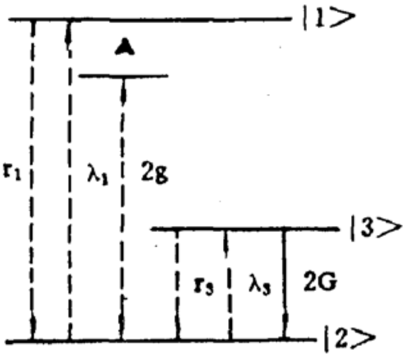

Fig. 1　V-type energy-level scheme

Scully 及其合作者研究的对象[1,2]包括简并量子拍激光系统[5]和原子相干建立于上能级的 Λ 型能级系统[1]. 本文将研究图1所示的V型能级系统，即 $|1\rangle\leftrightarrow|2\rangle$ 和 $|3\rangle\leftrightarrow|2\rangle$ 跃迁是偶极允许的. 这种能级系统最简单而又最普遍的一个例子是 $|2p\rangle\leftrightarrow|1s\rangle$ 和 $|1p\rangle\leftrightarrow|1s\rangle$ 系统. 考虑由外电磁场产生并建立下能级（能级 $|2\rangle$ 和能级 $|3\rangle$），原子相干（量子干涉）情况. 一束弱入射光以与原子跃迁 $|1\rangle\leftrightarrow|2\rangle$ 具有一定失谐的频率进入原子介质，分析该入射光在原子介质中的吸收和色散（折射）. 图1中 r_1 和 r_3 为自发衰变几率，λ_1 和 λ_3 为非相干泵浦速率，$2G$ 和 $2g$ 分别为电磁场和弱入射光的拉比频率.

$$g = g_0\exp(-i\nu t)\ , \qquad g_0 = dE_p^0. \tag{1}$$

式中 ν 为入射光频率，d 为原子偶极跃迁矩阵元，E_p^0 为弱入射光电场振幅.

原子密度矩阵运动方程可写为如下形式[7]

$$\begin{aligned}\dot{\rho} = &-r_1(A_{11}\rho + \rho A_{11} - 2\rho_{11}A_{22}) - r_3(A_{33}\rho + \rho A_{33} - 2\rho_{33}A_{22}) \\ &- \lambda_1(A_{22}\rho + \rho A_{22} - 2\rho_{22}A_{11}) - \lambda_3(A_{22}\rho + \rho A_{22} - 2\rho_{22}A_{33}) \\ &+ iG[A_{23} + A_{32},\ \rho] + ig[A_{12} + A_{21},\ \rho]\ ,\end{aligned} \tag{2}$$

收稿日期：1992年5月14日；收到修改稿日期：1992年6月17日

式中 $A_{ij} = |i\rangle\langle j|$. 计及入射光与原子跃迁 $|1\rangle \leftrightarrow |2\rangle$ 的频率失谐 $\Delta = \omega_{12} - \nu$，密度矩阵元运动方程可写为

$$\left.\begin{aligned}
\dot{\rho}_{12} &= -[(r_1 + \lambda_1 + \lambda_3) + i\Delta]\rho_{12} - iG\rho_{13} + ig(\rho_{22} - \rho_{11}) \ , \\
\dot{\rho}_{13} &= -[(r_1 + r_3) + i\Delta]\rho_{13} - iG\rho_{12} + ig\rho_{23} \ , \\
\dot{\rho}_{23} &= -(r_3 + \lambda_1 + \lambda_3)\rho_{23} + iG(\rho_{33} - \rho_{22}) + ig\rho_{13} \ , \\
\dot{\rho}_{11} &= -2r_1\rho_{11} + 2\lambda_1\rho_{22} + ig(\rho_{21} - \rho_{12}) \ , \\
\dot{\rho}_{22} &= 2r_1\rho_{11} - 2(\lambda_1 + \lambda_3)\rho_{22} + 2r_3\rho_{33} + iG(\rho_{32} - \rho_{23}) + ig(\rho_{12} - \rho_{21}) \ , \\
\dot{\rho}_{33} &= -2r_3\rho_{33} + 2\lambda_3\rho_{22} + iG(\rho_{23} - \rho_{32}) \ .
\end{aligned}\right\} \tag{3}$$

对弱入射光，ρ_{12} 只需计算到 g 的线性项. 故(3) 式后 4 式中含 g 项可以略去. 其稳态解为

$$\left.\begin{aligned}
&\rho_{11} = [G^2 + r_3(r_3 + \lambda_1 + \lambda_3)](\lambda_1/D) \ , \quad \rho_{22} = [G^2 + r_3(r_3 + \lambda_1 + \lambda_3)](r_1/D) \ , \\
&\rho_{33} = [G^2 + \lambda_3(r_3 + \lambda_1 + \lambda_3)](r_1/D) \ , \quad \rho_{23} = -\rho_{32} = iG(\rho_{33} - \rho_{22})/(r_3 + \lambda_1 + \lambda_3) \ , \\
&\tilde{\rho}_{12} = Re\tilde{\rho}_{12} + iIm\tilde{\rho}_{12} \ .
\end{aligned}\right\} \tag{4}$$

式中 $\tilde{\rho}_{12} = \rho_{12}\exp(i\nu t)$ 是 ρ_{12} 的振幅[1,2]，且

$$D = G^2(\lambda_1 + 2r_1) + (r_1\lambda_3 + r_3\lambda_1 + r_1r_3)(r_3 + \lambda_1 + \lambda_3) \ , \tag{5}$$

$$\left.\begin{aligned}
Re\tilde{\rho}_{12} &= \frac{g_0\Delta\{(\Delta^2 - E)(r_1 - \lambda_1)[G^2 + r_3(r_3 + \lambda_1 + \lambda_3)] + (2r_1 + r_3 + \lambda_1 + \lambda_3)F\}}{D[(E - \Delta^2)^2 + (2r_1 + r_3 + \lambda_1 + \lambda_3)^2\Delta^2]}, \\
Im\tilde{\rho}_{12} &= \frac{g_0\{(E - \Delta^2)F + (2r_1 + r_3 + \lambda_1 + \lambda_3)(r_1 - \lambda_1)[G^2 + r_3(r_3 + \lambda_1 + \lambda_3)]\Delta^2\}}{D[(E - \Delta^2)^2 + (2r_1 + r_3 + \lambda_1 + \lambda_3)^2\Delta^2]}
\end{aligned}\right\} \tag{6}$$

$$\left.\begin{aligned}
E &= G^2 + r_1^2 + r_1(r_3 + \lambda_1 + \lambda_3) + r_3(\lambda_1 + \lambda_3) \ , \\
F &= G^2(\lambda_3 - r_3)r_1 + [G^2 + r_3(r_3 + \lambda_1 + \lambda_3)](r_1 + r_3)(r_1 - \lambda_1) \ .
\end{aligned}\right\} \tag{7}$$

介质的极化由下式给出

$$P = Nd^*\rho_{12} \ , \tag{8}$$

式中 N 为原子密度，d 为对应于能级 1 和 2 之间的偶极矩阵元，为方便起见，取为实数(不失普遍性). 极化振幅 $\tilde{P} = P\exp(i\nu t)$. 原子介质对入射光的吸收由其虚部决定，而色散(折射)由其实部决定[1,2]. 因此方程(6)和(7)分别决定了介质对弱入射光的色散(折射)和吸收.

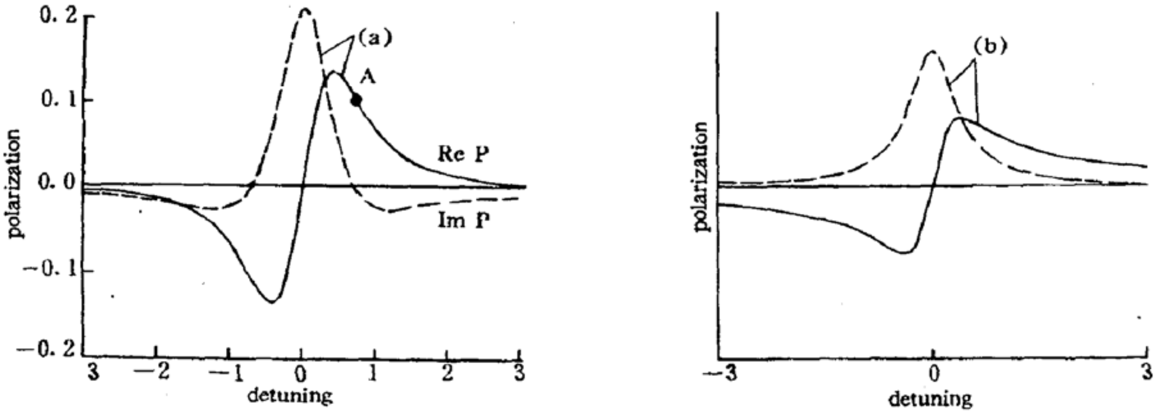

Fig. 2　Absorption-dispersion curve vs. detuning with atomic coherence

(a)　Ncluded. The polarization is plotted in unit of g_0/r and detuning in unit of r. At point A, $Im\tilde{\rho}_{12} = 0$, $Re\tilde{\rho}_{12} \neq 0$

(b)　Xcluded. Zero obserption is impossible in this case

为了清楚地显示原子相干对吸收-色散关系的影响，可以取如下一组物理参数 $r_1 = r_3 = \lambda_1 = 0.1r$，$2G = \lambda_3 = r$，并利用(5)式计算 Re $\tilde{\rho}_{12}$ 和 Im $\tilde{\rho}_{12}$. 得到的结果示于图 2(a). 为了比较，将通常的吸收-色散曲线(无原子相干)示于图 2(b). 从图 2 显见，原子相干的存在改变了通常的吸收-色散关系，使得弱入射光在一定失谐范围内，将经历吸收与反吸收(增益)的变化. 特别是在某一失谐处，Im $\tilde{\rho}_{12} = 0$，Re $\tilde{\rho}_{12} \neq 0$. 这种现象不存在于没有原子相干的情况(图 2(b)). 在数值计算过程中出现 Im $\tilde{\rho}_{12} = 0$，Re $\tilde{\rho}_{12} \neq 0$ 的现象，要求较大的 G 以及较大的 λ_3(或 r_3) 的值.

弱入射光在原子介质中的折射率 $n^2 - 1 \propto Re\tilde{P}$，因此，在 Im $\tilde{\rho}_{12} = 0$ 处 $\tilde{\rho}_{12} \neq 0$ 现象的出现使得弱入射光能够在不被吸收的情况下获得 $n > 1$ 的折射率. 这种利用量子干涉效应(原子相干)产生的现象不仅具有理论本身的意义，亦可望在许多实际问题中[3,4]获得应用.

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Influence of atomic coherence on the absorption-dispersion relation in V-type energy-level scheme

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(Received 14 May 1992; revised 17 June 1992)

Abstract

A new feature will be exhibited in the absorption-dispersion relation if quantum coherence is induced by an external field in the medium consisting of atoms of V-type energy-level configuration. In particular, when a weak light of a certain frequency travels in the medium, the refractive index can be larger than 1 where the absorption vanishes.

Key words atomic coherence, absorption-dispersion relation.