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微腔中单量子点的激光输出特性研究*

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摘　要:研究一个四能级量子点耦合到单模光学腔中的量子系统,利用系统的主方程作数值模拟计算微腔中单量子点的激光输出强度随非相干泵浦的变化关系.结果显示量子点在泵浦作用下激光的输出有一个阈值;且量子点和腔模耦合强度增强时,产生激光的阈值明显减小,输出激光的峰值却增大.当泵浦作用继续增强到一定程度,因激光能级间的相干性被过强的非相干泵浦所破坏,单量子点激光输出变为零----出现了淬灭现象.

关键词:激光;量子点;非相干泵浦;淬灭

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0　引言

1986 年东京技术研究所的 Masahiro Asada 及其合作者在东京大学的 Yasuhito Arakawa 早期工作的基础上,预言了量子点激光器-激活区含有大量相等尺寸的量子点将具有更好性能[1-2].如果某种半导体材料晶体在空间三维上的尺寸大小均与载流子在该材料中的德布罗意波长或电子的平均自由程相当或更小,而同时该晶体又被禁带宽度更大的垒层材料包围,这就构成了量子点结构,以量子点为有源区的激光器就称为量子点激光器.自 1994 年第一个基于应变自组装 InAs/ GaAs 量子点的激光器[3]研制成功以来,研究进展十分迅速,尤其是在大功率量子点激光器的研发方面取得了突破,工作寿命已达数千小时.而且以量子点为有源区的半导体量子点激光器比量子阱、量子线激光器具有更好的激射特性,有可能实现更低的阈值电流密度、更高的特征温度、高的发光效率和微分增益、窄的光谱线宽[4-7],还可能产生许多特殊的物理性质如量子限制斯塔克(Stark)效应、非线性光增益[8-10]、空间光谱烧孔[11-13]库仑势垒等,故量子点激光器的研制愈来愈受到人们的重视.

此外,常规激光器的尺寸受到波长的限制,其实现尺度不可能太小;而单量子点微腔激光器可实现的尺度则为微米级,且可以实现电抽运.单量子点相当于单个原子,但由于其体积比原子大得多,因而具有大的电偶极矩.再加上腔内一个光子所对应的腔内电场强度与腔体积的平方根成反比,这两个因素综合起来使得量子点与光子的耦合常量大,可进入强耦合的范畴;且还可以形成光子与量子点状态的纠缠,挤压态等,这在量子计算和量子信息处理中可能获得应用[14-17];单光子源还是实现量子密码通讯的条件.因而它在纳米电子学、光电子学、量子计算和生命科学等方面也有着重要的应用前景.

本文研究一个四能级量子点在单模光学腔中的量子系统,通过数值求解主方程的方法讨论激光输出的特性.

1　物理模型与理论计算

图 1 是一个四能级量子点在单模光学腔中的量子系统图.图中 Γ 是非相干泵浦率,量子点能级间的升降由满足反对易的升降算符描述,下降算符是 σ_{ij}^{-},上升算符是 σ_{ij}^{+}.腔模与量子点激光跃迁是共振的,腔模的玻色湮灭算符产生算符分别为 a,a^{+};激光跃迁通过电偶极距与腔模作用.在旋波近似下,Jaynes-Cummings 模型[18]的哈密顿量是

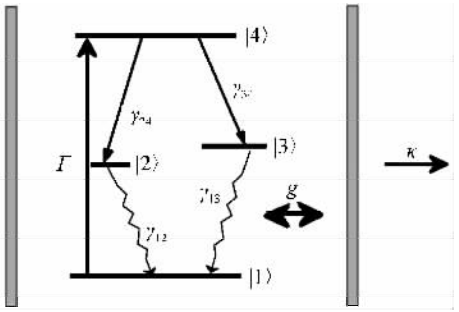

图 1　四能级量子点能级分布

Fig. 1　The energy level schematic diagram of a four-level quantum dot

$$H_{JC} = \mathrm{i}\hbar g(a^{+}\sigma_{13}^{-} - a\sigma_{13}^{+}) \tag{1}$$

激光对应于 1、3 能级之间,g 是量子点和腔模的耦合强度

$$g = (\frac{3\pi\gamma_{13}c^{3}}{2\omega^{2}})^{1/2}|u(\boldsymbol{r})| \tag{2}$$

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式中 γ_{13} 是激光能级间的衰减率，ω 是激光的跃迁频率，$u(\boldsymbol{r})$ 是腔的模式函数．量子点和腔模可都耦合到相应的库，腔模通过腔镜的损失而导致衰减，衰减率是 2κ，量子点由能级 i 到能级 j 而辐射到腔外的自发辐射辐射率是 γ_{ij}（其中 $1\leqslant i\leqslant 4$；$1\leqslant j\leqslant 4$），在相互作用表象中，四能级量子点的主方程[19]为

$$\begin{aligned}
&\frac{\mathrm{d}\rho}{\mathrm{d}t}=\frac{[H_{JC},\rho]}{\mathrm{i}\hbar}+L_{\mathrm{C}}\rho+L_{\mathrm{P}}\rho+\sum_{\substack{i,j=1\\(i\neq j,i\langle j)}}^{4}L_{\mathrm{A}_{ij}}\rho\\
&L_{\mathrm{C}}\rho=\kappa(2a\rho a^{+}-a^{+}a\rho-\rho a^{+}a)\\
&L_{\mathrm{A}_{ij}}\rho=\frac{\gamma_{ij}}{2}(2\sigma_{ij}^{-}\rho\sigma_{ij}^{+}-\sigma_{ij}^{+}\sigma_{ij}^{-}\rho-\rho\sigma_{ij}^{+}\sigma_{ij}^{-})\\
&L_{\mathrm{P}}\rho=\frac{\Gamma}{2}(2\sigma_{14}^{+}\rho\sigma_{14}^{-}-\sigma_{14}^{-}\sigma_{14}^{+}\rho-\rho\sigma_{14}^{-}\sigma_{14}^{+})
\end{aligned}\tag{3}$$

从主方程(3)可以得到系统任意算符 $\langle\theta\rangle$ 期待值的运动方程为

$$\frac{\mathrm{d}}{\mathrm{d}t}\langle\theta\rangle=\frac{\langle[\theta,H_{JC}]\rangle}{\mathrm{i}\hbar}+\mathrm{Tr}(\theta L\rho)\tag{4}$$

式中 $L\rho$ 描绘了主方程(3)右边的所有消耗项，腔场振幅 $\langle a\rangle$，量子点算符 $\langle\sigma_{ij}^{-}\rangle$ 的期待值方程为

$$\begin{aligned}
&\frac{\mathrm{d}}{\mathrm{d}t}\langle a\rangle=-\kappa\langle a\rangle+g\langle\sigma_{13}^{-}\rangle\\
&\frac{\mathrm{d}}{\mathrm{d}t}\langle\sigma_{12}^{-}\rangle=g\langle a\sigma_{23}^{+}\rangle-\frac{\gamma_{12}+\Gamma}{2}\langle\sigma_{12}^{-}\rangle\\
&\frac{\mathrm{d}}{\mathrm{d}t}\langle\sigma_{13}^{-}\rangle\ g{=}\langle a\sigma_{3}-a\sigma_{1}\rangle-\frac{\Gamma+\gamma_{13}}{2}\langle\sigma_{13}^{-}\rangle\\
&\frac{\mathrm{d}}{\mathrm{d}t}\langle\sigma_{14}^{-}\rangle=g\langle a\sigma_{34}^{-}\rangle-\frac{1}{2}(\Gamma+\gamma_{14}+\gamma_{24}+\gamma_{34})\langle\sigma_{14}^{-}\rangle\\
&\frac{\mathrm{d}}{\mathrm{d}t}\langle\sigma_{24}^{-}\rangle=-\frac{1}{2}(\gamma_{12}+\gamma_{14}+\gamma_{24}+\gamma_{34})\langle\sigma_{24}^{-}\rangle\\
&\frac{\mathrm{d}}{\mathrm{d}t}\langle\sigma_{34}^{-}\rangle=-g\langle a^{+}\sigma_{14}^{-}\rangle-\frac{1}{2}(\gamma_{13}+\gamma_{14}+\\
&\qquad\gamma_{23}+\gamma_{24}+\gamma_{34})\langle\sigma_{34}^{-}\rangle\\
&\frac{\mathrm{d}}{\mathrm{d}t}\langle\sigma_{1}\rangle=g\langle a^{+}\sigma_{13}^{-}+a\sigma_{13}^{+}\rangle-\Gamma\langle\sigma_{1}\rangle+\gamma_{12}\langle\sigma_{2}\rangle+\\
&\qquad\gamma_{13}\langle\sigma_{3}\rangle\\
&\frac{\mathrm{d}}{\mathrm{d}t}\langle\sigma_{2}\rangle=-\gamma_{12}\langle\sigma_{2}\rangle+\gamma_{24}\langle\sigma_{4}\rangle\\
&\frac{\mathrm{d}}{\mathrm{d}t}\langle\sigma_{3}\rangle=-g\langle a^{+}\sigma_{13}^{-}+a\sigma_{13}^{+}\rangle-\gamma_{13}\langle\sigma_{3}\rangle+\gamma_{34}\langle\sigma_{4}\rangle\\
&\langle\sigma_{1}\rangle+\langle\sigma_{2}\rangle+\langle\sigma_{3}\rangle+\langle\sigma_{4}\rangle=1
\end{aligned}\tag{5}$$

期待值 $\langle\sigma_i\rangle\equiv\langle\sigma_{ii}\rangle$ 描述的是电子处于量子点能级 $|i\rangle$ 的几率．考虑半经典近似情况，忽略量子点算符和场算符的关联，如方程(5)中的 $\langle a\sigma_{34}^{-}\rangle$ 可以写为：$\langle a\sigma_{34}^{-}\rangle=\langle a\rangle\langle\sigma_{34}^{-}\rangle$．可以得到腔内光子数算符的期望值为[19]

$$\langle n\rangle=\frac{\gamma_{34}\langle\sigma_{4}\rangle-\gamma_{13}\langle\sigma_{3}\rangle}{2\kappa}=-\frac{B\Gamma\gamma_{13}\gamma_{24}+(B-}{2\kappa[\Gamma\gamma_{24}+}\rightarrow$$

$$\leftarrow\frac{1)\Gamma\gamma_{12}\gamma_{34}+\gamma_{13}\gamma_{12}[B\Gamma+(1+B)(\gamma_{24}+\gamma_{34})]}{\gamma_{12}(\Gamma+2\gamma_{24}+2\gamma_{34})]}\tag{6}$$

式中

$$B=\frac{\kappa(\Gamma+\gamma_{13})}{2g^{2}}\tag{7}$$

2 结果与分析

图2是量子点和腔模耦合强度分别为 $g=1.0$ 和 $g=1.5$ 时腔内输出光子数随泵浦率 Γ 的变化曲线，横坐标为非相干泵浦 Γ，纵坐标为腔内光子数 $\langle n\rangle$；相应参量取值为：$\gamma_{12}=0.8$，$\gamma_{24}=1.0$，$\gamma_{13}=1.0$，$\gamma_{34}=0.5$，$\kappa=0.01$．输出平均光子数曲线显示：量子点在弱的泵浦作用下没有激光输出而是有一个泵浦阈值；当越过阈值后输出激光强度随泵浦增大而急剧增大[20]，但不是线性增大，而是增大到一个峰值后开始减小，当泵浦作用继续增强到一定程度，整个激光输出变为零．这个现象可以从系统方程组(5)看到端倪，$\langle\sigma_{13}^{-}\rangle$ 中的衰减与泵浦率 Γ 和自发辐射 γ_{13} 之和有关，当泵浦大到使极化项 $\langle\sigma_{13}^{-}\rangle$ 时变率为零甚至为负时，淬灭就可能发生．激光能级间的相干性被过强的非相干泵浦所破坏，出现了淬灭现象．

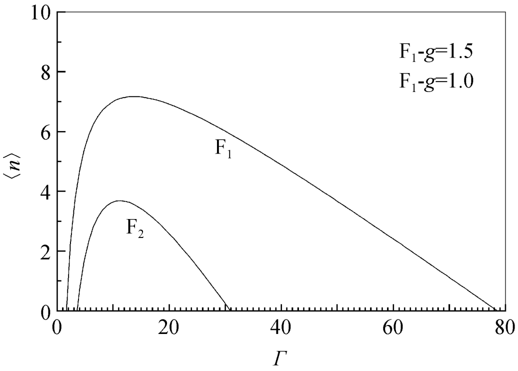

图2 横坐标为非相干泵浦率 Γ，纵坐标为腔内光子数 $\langle n\rangle$

Fig. 2 The mean number of photons $\langle n\rangle$ in the cavity vs incoherent pumping rate Γ

从图2还可以明显看出，耦合强度越大，激光增益越快且输出光强也越大．不同的耦合强度产生激光的阈值也是不一样的：耦合强度 $g=1.5$ 的阈值是在1和2之间；耦合强度 $g=1.0$ 的阈值较大，在泵浦率为3时还没有激光输出．不同的耦合强度到达淬灭时的泵浦强度也是不同的，耦合强度越大、到达淬灭时的泵浦强度也越大，如耦合强度 $g=1.0$ 的淬灭发生在泵浦率为31而耦合强度 $g=1.5$ 的泵浦率则大致在78.

3 结论

本文研究了一个四能级量子点在单模光学腔中的量子系统，数值计算的结果显示：量子点在泵浦作用下激光输出有一个阈值；且量子点和腔模耦合强

度增强时,激光产生的阈值明显减小,输出激光的峰值却增大.当非相干泵浦作用继续增强到一定程度,激光能级间的相干性被过强的非相干泵浦所破坏,因而单量子点激光出现了淬灭现象.

参考文献

[1] ASADA M, MIYANOTO Y, SUEMATSU Y. Gain and the threshold of three dimensional quantum-box lasers[J]. *IEEE J Quantum Electron*, 1986, **QE-22**(9): 1915-1921.

[2] ARKAWA Y, SAKAKI H. Muhidimensional quantum weII laser and temperature dependence of its threshold CUlTent [J]. *Appl Phys Lett*, 1982, **40**(11): 939-941.

[3] KIRSTAEDTER N, LEDENTSOVN N, GRUNDMANN M, *et al*. Low threshold, large to injection laser emission from (In-GaAs) quantum dots[J]. *Electron Lett*, 1994, **30**(17): 14l6-14l8.

[4] ZHANG Dang-wei, ZHANG Jing-wen, HOU xun. X-ray differaction from self-organized quantum-dot [J]. *Acta Photonica Sinica*, 2002, **31**(7): 837-840.
张党卫,张景文,侯洵. 利用X射线衍射分析自组织生长的量子点结构[J]. 光子学报, 2002, **31**(7): 837-840.

[5] MUKAI K. 1.3 μm lasing characteristics of self-assembled InGaAs-GaAs quantum dots[J]. *IEEE Journal of Quantum Electronics*, 2000, **36**(4): 472-478.

[6] ZHAO Zheng, PAN Wei, LUO Bin, *et al*. Theoretical analyses of semiconductor optical amplifiers based on vertical-cavity resonator[J]. *Acta Photonica Sinica*, 2004, **33**(12): 1421-1424.
赵峥,潘炜,罗斌,等. 基于垂直谐振腔结构的半导体光放大器理论分析[J]. 光子学报, 2004, **33**(12): 1421-1424.

[7] BHATTACHARYA P. In(Ga)As/GaAs self-organized quantum dot lasers: DC and small-signal modulation properties [J]. *IEEE Transcations on Electron Devices*, 1999, **46**(5): 871-883.

[8] CHEN Jun, LIU Zheng-dong, ZHENG Jun, *et al*. Effect of vacuum-induced coherence in a four-level atomic system[J]. *Acta Physica Sinica*(adopted).
陈峻,刘正东,郑军,等. 基于量子干涉效应的四能级原子系统中的 Vacuum-Induced Coherence 效应[J]. 物理学报(已录用).

[9] AKIYAMA T. Nonlinear gain dynamics in quantum-dot optical amplifiers and its application to optical communication devices[J]. *IEEE Journal of Quantum Electronics*, 2001, **37**(8): 1059-1064.

[10] ZHANG Li-ying, LIU Zheng-dong, CHEN Jun. The electromagnetically induced transparency in the Y-type four-level atom system at low light levels[J]. *Science in China*, 2005, **35**(6): 566-572.
张丽英,刘正东,陈俊. 弱光场下Y型四能级原子系统的电磁感应透明[J]. 中国科学, 2005, **35**(6): 566-572.

[11] ELISEEV P, LI H. Tunable grating-coupled laser oscillation and spectral hole burning in an InAs quantum-dotlaser diode [J]. *IEEE Journal of Quantum Electronics*, 2000, **36**(4): 479-484.

[12] ASRVAN L V, SURIS R A. Longitudinal spatial liole buring in a quantum-dot laser [J]. *IEEE Journal of Quantum Electronics*, 2000, **36**(10): 1151-1161.

[13] CHEN Jun, LIU Zheng-dong, YOU Su-ping. The hole burning and optical bistability of quasi-Λ-type four-level atom system[J]. *Acta Physica Sinica*, 2006, **55**(12): 6410-6414.
陈峻,刘正东,尤素萍. 准Λ型四能级原子系统中的烧孔和光学双稳现象[J]. 物理学报, 2006, **55**(12): 6410-6414.

[14] BIOLATTI E, AMICO I D, ZANARDIPET, *et al*. Electro-optical properties of semiconductor quantum dots: Application to quantum information processing [J]. *Phys Rev B*, 2002, **65**: 075306.

[15] WANG Zhao-ying, HU Zhi-yong, BAO huan-min, *et al*. Tunable multi-wavelength fiber laser based on semiconductor optical amplifier[J]. *Acta Photonica Sinica*, 2006, **35**(3): 321-324.
王肇颖,胡智勇,包焕民,等. 基于半导体光放大器的可调谐多波长光纤激光器[J]. 光子学报 2006, **35**(3): 321-324.

[16] LEDENTSOV N N, USTINOV V M, BOROVKOV A I, *et al*. Direct formation of vertically coupled quantum dots in stranski-krastanow growth[J]. *Phys Rev B*, 1996, **54**: 8743.

[17] PARK Gyoungwen, SHCHEKING Oleg B, SEHASTION, *et al*. The study of single quantum dot laser's particular output property in microcavity[J]. *Appl Phys Lett*, 1999, **75**: 3267.

[18] SMITH A M, GARDINER C W. Three-level atom laser model with results and applications[J]. *Phys Rev A*, 1990, **41**: 2730.

[19] MU Yi, SAVAGE C M. One-atom lasers[J]. *Phys Rev A*, 1992, **46**: 5944.

[20] LIAO Qing-hong, LIU Zheng-dong, YOU Su-ping, *et a*1. The study of a single quantum dot lasers in microcavity[J]. *Acta Sinica Quantum Optica*(accepted).
廖庆洪,刘正东,尤素萍,等. 单量子点微腔激光器的研究[J]. 量子光学学报(已录用).

The Study of a Single Quantum Dot Laser′s Particular Output Property in Microcavity

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Abstract: The quantum system under investigation is a four-level QD (quantum dot) coupled a single mode of an optical microcavity. By the numerical calculation method of the quantum-optical master equations the intensity of a single QD laser′s evolution with the variation of the incoherent pumping rate was investigated. The results display that there is a threshold for Laser′s output under the action of the incoherent pumping. The stronger of the coupling strength between the QD and mode, the smaller of threshold, and the larger peak value of Laser′s output. At the sufficiently high pump rates the lasing turns off to zero, because the coherence between the laser levels is destroyed. Self-quenching behavior appears.

Key words: Laser; Quantum dot; Incoherent pumping; Self-quenching

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