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半导体光放大器的非简并时延四波混合理论*

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摘要： 用二能级宽带模型研究了半导体光放大器(SOA)中非简并相共轭四波混合信号强度随时间延迟的变化规律。结果表明，对这种情形的非简并四波混合共轭信号强度随时间延迟 τ 变化表明为载流子脉动，且脉动信号以退相速率衰减。鉴于目前用简并四波混合对半导体光放大器超快过程的测量需要大功率激光器作激发源、大光学实验平台和复杂的探测设备的情况下，提出了基于全光通信器件构成非简并四波混合观测半导体光放大器载流子脉动、退相时间新方法，这不仅便于选取抽运与探测光源波长(光通信窗口波长)，而且可使测试设备微型化。

关键词： 非线性光学；半导体光放大器；四波混合；载流子脉动；退相时间测量；全光纤通信器件

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Theory of Delayed-Time Non-Degenerate Four-Wave Mixing Semiconductor Optical Amplifier

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Abstract: The signal intensity of phase-conjugation-type delayed-time four-wave mixing (TDFWM) with incoherent light is studied based on the two-level broad band model of semiconductor optical amplifier (SOA). The theoretical results show that the signal intensity not only decays with the dephasing rate of SOA but also pulsates with the delay time. Since the experimental investigation of both the carrier pulsation and the dephasing time using degenerate four wave mixing are limited only in the application cases of high-power laser, large optical experimental platform and sophisticated detection devices at present, a novel scheme composed of all-optical communication devices is proposed based on non-degenerate four-wave mixing. This means that both pump wavelength and probe wavelength not only are easily selected but also an experimental setup can be minimized.

Key words: nonlinear optics; semiconductor optical amplifier; four-wave mixing; carrier pulsation; measurement of dephasing time; all-optical communication devices

1 引　　言

就半导体光放大器近简并四波混合(NFWM)波长转换[1~6]而言，由于抽运光与信号光频率不同，导致载流子脉动。假如，抽运光的圆频率为 ω_p，信号光圆频率为 ω_s，则载流子脉动频率为 $\Delta=\omega_p-\omega_s$，所对应的脉动时间为 $T_p=2\pi/\Delta$。在 ω_p 与 ω_s 相差不大的情况下，T_p 典型值在 100～200 ps。

众所周知，载流子脉动属带内过程，外光场对注入载流子调制的结果形成一动态光栅[7,8]。显然，当失谐量 $\Delta=0$ 时，载流子脉动消失使动态光栅

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退化成稳态光栅。这意味着：当我们利用简并时延四波混合[9~13]（TDFWM）研究带内过程时，不涉及到载流子脉动，共轭波信号主要来自于稳态粒子数布居光栅对探测光的衍射。因而，在实验上只能测出带内或带间载流子弛豫时间。另一方面，由于在简并时延四波混合中抽运光、探测光及共轭光频率相同，因此，很难从光纤中取出所需的共轭光，这就给利用全光纤通信器件进行时延四波混合设计使半导体光放大器超快时间实验装置微型化带来相当大的困难。出于对载流子观察和基于全光纤通信器件的双重考虑，本文基于宽带二能级模型对半导体光放大器进行了非简并时延四波混合理论研究，其结果表明：在共轭光信号中不仅能观测到载流子脉动现象，而且能测量出带间弛豫时间。

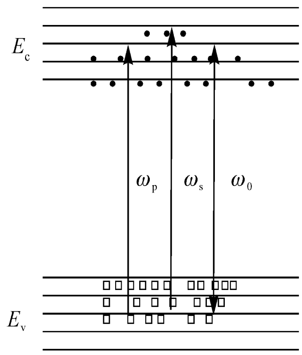

Fig. 1 The broad band model of SOA. E_c and E_v denote the energys in conduction and valence bands, respectively; ω_0 is the central transition frequency between conduction and valence bands, ω_p and ω_s are the angular frequency of pump and signal beam, respectively

2 模型与运动方程

对于 InGaAsP/InP 异质结半导体光放大器，其能带结构可近似用图1所示的宽带二能级模型进行描述。当有载流子注入时，在导带中有大量的自由电子，而在价带中有大量的空穴。设作用在半导体光放大器中的总光场的电场强度为 $E(t)$，则系统的哈密顿量为

$$H = H_0 - \mu E(t), \tag{1}$$

式中 H_0 为半导体光放大器自身的哈密顿量，μ 为偶极算符。其密度矩阵满足刘维尔(Liouville)方程[14]

$$\frac{\partial \rho}{\partial t} = \frac{\mathrm{i}}{\hbar}[\rho, H] + R_{\mathrm{coll}}, \tag{2}$$

式中

$$R_{\mathrm{coll}} = -\gamma^{\mathrm{l}}(\rho - f) - \gamma^{\mathrm{h}}(\rho - f^{\mathrm{L}}) - \gamma^{\mathrm{s}}(\rho - f^{\mathrm{eq}}), \tag{3}$$

式中 ρ 的对角矩阵元代表电子(空穴)在导带(价带)中的占有几率，它与电子(空穴)波矢 $\boldsymbol{k}$ 有关；其非对角元与偶极跃迁相联系。式中右边第一项表示由于载流子-载流子散射过程引起的以速率 γ^{l} 趋于费米分布函数 f。式中第二项表示由于载流子-纵波光学声子引起的以速率 γ^{h} 趋于晶格温度为 T_{L} 费米分布函数 f^{L}，右边最后一项表示以速率 γ^{s} 趋于温度函数 f^{eq}。当外场与半导体光放大器相互作用较弱时，$-\mu E(t)$ 可当作微扰。$-\mu E(t)$ 当作微扰，可对 ρ 按级数展开 $\rho = \rho^{(0)} + \rho^{(1)} + \rho^{(2)} + \cdots$，由(1)式经微扰链 $\rho^{(0)} \to \rho^{(1)} \to \rho^{(2)} \to \rho^{(3)}$ 可得到与四波混合相关的第三阶偶极矩阵元：

$$\begin{aligned}\rho_{\mathrm{cv}}^{(3)} = & [2(\rho_{\mathrm{c}}^{(0)} - \rho_{\mathrm{v}}^{(0)})/(\mathrm{i}\hbar)^3]\,|\mu^{\mathrm{cv}}|^2\mu_{\mathrm{cv}}\int_{-\infty}^{t}\mathrm{d}t_3\int_{-\infty}^{t_3}\mathrm{d}t_2\int_{-\infty}^{t_2}\mathrm{d}t_1\exp[-\gamma_2(t - t_3 + t_2 - t_1) - \gamma_1(t_3 - t_2)]\times \\ & \{E(t_3)E(t_2)E^*(t_1)\exp[-\mathrm{i}\omega_0(t - t_3 - t_2 + t_1)] + \\ & E(t_3)E^*(t_2)E(t_1)\exp[-\mathrm{i}\omega_0(t - t_3 + t_2 - t_1)] - \gamma_1(\rho_{\mathrm{c}}^{(0)} - \rho_{\mathrm{v}}^{(0)})\},\end{aligned} \tag{4}$$

式中 $\rho_{\mathrm{c}}^{(0)}$、$\rho_{\mathrm{v}}^{(0)}$ 分别为初始时刻电子在导带中的占有概率和空穴在价带中的占有概率。μ_{cv} 为带间偶极跃迁矩阵元。γ_1、γ_2 为纵向(带内)弛豫速率和横向(带间)弛豫速率。

3 非简并四波混合

如果实验时采用图2所示的相位共轭型四波混合则作用在半导体光放大器中的总光场强度为

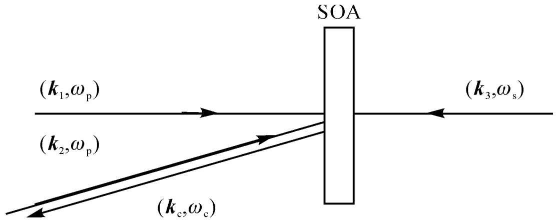

Fig. 2 Near-degeneration phase-conjugation four-wave mixing

$$E(t)=\varepsilon_p\exp[i(\boldsymbol{k}_1\cdot\boldsymbol{r}-\omega_p t)]+\varepsilon_p(t+\tau)\exp\{i[\boldsymbol{k}_2\cdot\boldsymbol{r}-\omega_p(t+\tau)]\}+\varepsilon\exp[i(\boldsymbol{k}_3\cdot\boldsymbol{r}-\omega_s t)],\tag{5}$$

式中 $\varepsilon_p(t)$ 为宽带脉冲慢变化振幅，ε 为窄带脉冲振幅。τ 为脉冲($\boldsymbol{k}_2,\omega_p$) 相对脉冲($\boldsymbol{k}_1,\omega_p$) 的时间延迟。将(5)式代入(4) 式，作旋转波近似，可得 $\boldsymbol{k}_c=\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3$，频率为 $\omega_c=2\omega_p-\omega_1$ 的相共轭矩阵元：

$$\begin{aligned}\rho_{cv}^{(3)}(t)\propto|\mu_{cv}|^2\mu_{cv}\exp(-i\omega_p\tau)\int_{-\infty}^{t}dt_3\int_{-\infty}^{t_3}dt_2\int_{-\infty}^{t_2}dt_1\exp[-\gamma_2(t-t_3+t_2-t_1)-\gamma_1(t_3-t_2)]\times\\ \{[\varepsilon_p(t_3)\varepsilon_p(t_2+\tau)+\varepsilon_p(t_3+\tau)\varepsilon_p(t_2)]\varepsilon^*\exp[-i\Delta\omega(t-t_3-t_2+t_1)-i\omega_p(t+t_1)+i\omega_s t_1]+\\ [\varepsilon_p(t_3)\varepsilon_p(t_1+\tau)+\varepsilon_p(t_3+\tau)\varepsilon_p(t_1)]\varepsilon^*\exp[-i\Delta\omega(t-t_3+t_2-t_1)-i\omega_p(t+t_2)+i\omega_s t_2]\},\end{aligned}\tag{6}$$

式中右边前两项对应于光子回波，而后两项对应于自感应透明[15]，故可忽略后两项。利用公式[16]

$$P^{(3)}(t)=(1/V)\mathrm{Tr}[\mu\rho^{(3)}],\tag{7}$$

式中 V 为半导体光放大器有源层体积，并假设带间自发射谱线型满足洛仑兹分布[17]：

$$L(\Delta\omega)=\frac{1}{\pi}\frac{\gamma_2}{(\Delta\omega)^2+\gamma_2^2},\tag{8}$$

式中 ω_1、ω 分别为外激发场中心圆频率和半导体光放大器发射光圆频率。$\gamma_2=(\gamma_c+\gamma_v)/2$ 由导带和价带中载流子-载流子散射和载流子-纵波光学声子散射速率决定。并考虑到整个增益带宽的贡献，则三阶电极化强度进一步写成

$$\begin{aligned}P^{(3)}(\boldsymbol{k}_c,\omega_c;t,\tau)\propto\int_{-\infty}^{\infty}d(\Delta\omega)L(\Delta\omega)\int_{-\infty}^{t}dt_3\int_{-\infty}^{t_3}dt_2\int_{-\infty}^{t_2}dt_1\exp[-\gamma_2(t-t_3+t_2-t_1)-\gamma_1(t_3-t_2)]\times\\ [\varepsilon_p(t_3)\varepsilon_p(t_2+\tau)+\varepsilon_p(t_3+\tau)\varepsilon_p(t_2)]\varepsilon^*\exp[-i\Delta\omega(t-t_3-t_2+t_1)-i\omega_p(t+t_1)+i\omega_s t_1],\end{aligned}\tag{9}$$

对积分变量 $\Delta\omega=\omega-\omega_1$ 积分，并作变量代换 $\tau_3=t-t_3,\tau_2=t_3-t_2,\tau_1=t_2-t_1$，(9) 式可简化成

$$\begin{aligned}P^{(3)}(\boldsymbol{k}_s,\omega_s;t,\tau)\propto&\int_0^{\infty}d\tau_3\int_0^{\infty}d\tau_2\int_0^{\infty}d\tau_1\exp(-\gamma_2\tau_3-\gamma_1\tau_2)\times\\ &[\varepsilon_p(t-\tau_3)\varepsilon_p(t-\tau_3-\tau_2+\tau)+\varepsilon_p(t-\tau_3+\tau)\varepsilon_p(t-\tau_2-\tau_1)]\varepsilon^*\times\\ &\exp[-i(2\omega_1-\omega_2)t+i(\omega_1-\omega_2)(\tau_3+\tau_2)+i(\omega_1-\omega_2)\tau_1].\end{aligned}\tag{10}$$

利用式

$$I(\tau)\propto\langle|P^{(3)}(k_s,\omega;t,\tau)|^2\rangle,\tag{11}$$

式中"〈〉"表示复随机变量的统计平均。由此，与时间延迟 τ 有关的信号强度为

$$\begin{aligned}I(\tau)\propto|\varepsilon|^2\int_0^{\infty}d\tau_3\int_0^{\infty}d\tau_2\int_0^{\infty}ds_3\int_0^{\infty}ds_2\exp[-2\gamma_2(\tau_3+s_3)-\gamma_1(\tau_2+s_2)]\times\\ [\langle\varepsilon_p(t-\tau_3)\varepsilon_p(t-\tau_3-\tau_2+\tau)\varepsilon_p^*(t-s_3)\varepsilon_p^*(t-s_3-s_2+\tau)\rangle+\\ \langle\varepsilon_p(t-\tau_3)\varepsilon_p(t-\tau_2-\tau_2+\tau)\varepsilon_p^*(t-s_3+\tau)\varepsilon_p^*(t-s_2-s_2)\rangle+\\ \langle\varepsilon_p(t-\tau_3+\tau)\varepsilon_p(t-\tau_3-\tau_2)\varepsilon_p^*(t-s_3)\varepsilon_p^*(t-s_3-s_2+\tau)\rangle+\\ \langle\varepsilon_p(t-\tau_3+\tau)\varepsilon_p(t-\tau_3-\tau_2)\varepsilon_p^*(t-s_3+\tau)\varepsilon_p^*(t-s_3-s_2)\rangle].\end{aligned}\tag{12}$$

由于宽带光类似于热辐射源，而人们通常把这类光源看作复随机光束。按照复随机统计规律[18]，(12)式右边与四阶自相关函数的统计平均可写成二阶自相关函数的形式：

$$\begin{aligned}&\langle\varepsilon_p(t-\tau_3)\varepsilon_p(t-\tau_3-\tau_2+\tau)\varepsilon_p^*(t-s_3)\varepsilon_p^*(t-s_3-s_2+\tau)\rangle=\\ &\langle\varepsilon_p(t-\tau_3)\varepsilon_p^*(t-s_3)\rangle\langle\varepsilon_p(t-\tau_3-\tau_2+\tau)\varepsilon_p^*(t-s_3-s_2+\tau)\rangle+\\ &\langle\varepsilon_p(t-\tau_3)\varepsilon_p^*(t-s_3-s_2+\tau)\rangle\langle\varepsilon_p(t-\tau_3-\tau_2+\tau)\varepsilon_p^*(t-s_3)\rangle=\\ &f(\tau_3-s_3)f(\tau_3+\tau_2-s_3-s_2)+f(\tau_3-s_3-s_2-\tau)f(\tau_3+\tau_2-s_3-\tau),\end{aligned}\tag{13a}$$

$$\begin{aligned}&\langle\varepsilon_p(t-\tau_3)\varepsilon_p(t-\tau_3-\tau_2+\tau)\varepsilon_p^*(t-s_3+\tau)\varepsilon_p^*(t-s_3-s_2)\rangle=\\ &\langle\varepsilon_p(t-\tau_3)\varepsilon_p^*(t-s_3+\tau)\rangle\langle\varepsilon_p(t-\tau_3-\tau_2+\tau)\varepsilon_p^*(t-s_3-s_2)\rangle+\\ &\langle\varepsilon_p(t-\tau_3)\varepsilon_p^*(t-s_3-s_2)\rangle\langle\varepsilon_p(t-\tau_3-\tau_2+\tau)\varepsilon_p^*(t-s_3+\tau)\rangle=\\ &f(\tau_3-s_3-\tau)f(\tau_3+\tau_2-s_3-s_2-\tau)+f(\tau_3-s_3-s_2)f(\tau_3+\tau_2-s_3),\end{aligned}\tag{13b}$$

$$\langle\varepsilon_p(t-\tau_3+\tau)\varepsilon_p(t-\tau_3-\tau_2)\varepsilon_p^*(t-s_3)\varepsilon_p^*(t-s_3-s_2+\tau)\rangle=$$
$$\langle\varepsilon_p(t-\tau_3+\tau)\varepsilon_p^*(t-s_3)\rangle\langle\varepsilon_p(t-\tau_3-\tau_2)\varepsilon_p^*(t-s_3-s_2+\tau)\rangle+$$
$$\langle\varepsilon_p(t-\tau_3+\tau)\varepsilon_p^*(t-s_3-s_2+\tau)\rangle\langle\varepsilon_p(t-\tau_3-\tau_2)\varepsilon_p^*(t-s_3)\rangle=$$
$$f(\tau_3-s_3-\tau)f(\tau_3+\tau_2-s_3-s_2-\tau)+f(\tau_3-s_3-s_2)f(\tau_3+\tau_2-s_3),\qquad(13c)$$
$$\langle\varepsilon_p(t-\tau_3+\tau)\varepsilon_p(t-\tau_3-\tau_2)\varepsilon_p^*(t-s_3+\tau)\varepsilon_p^*(t-s_3-s_2)\rangle=$$
$$\langle\varepsilon_p(t-\tau_3+\tau)\varepsilon_p^*(t-s_3+\tau)\rangle\langle\varepsilon_p(t-\tau_3-\tau_2)\varepsilon_p^*(t-s_3-s_2)\rangle+$$
$$\langle\varepsilon_p(t-\tau_3+\tau)\varepsilon_p^*(t-s_3-s_2)\rangle\langle\varepsilon_p(t-\tau_3-\tau_2)\varepsilon_p^*(t-s_3+\tau)\rangle=$$
$$f(\tau_3-s_3)f(\tau_3+\tau_2-s_3-s_2)+f(\tau_3-s_3-s_2-\tau)f(\tau_3+\tau_2-s_3-\tau).\qquad(13d)$$

忽略(13)式中与 τ 无关项[通常只对 $I(\tau)$ 的贡献是常量背景]。考虑到宽带高斯光束的二阶自相关函数 $f(t)=\exp[-(t/\tau_c)^2]$，其中，$\tau_c=1/\sqrt{\pi}(\Delta\Omega)$ 为光束的自相关时间。当光束的线宽 $\Delta\Omega$ 很大以致 $\tau_c\ll T_1$，T_2（T_1、T_2 分别为半导体光放大器的带内弛豫时间和退相时间）时，$f(t)\rightarrow\delta(t)$。将狄拉克函数 $\delta(t)$ 写成

$$\delta(t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\mathrm{d}\omega\exp(\mathrm{i}\omega t),\qquad(14)$$

则与时间延迟 τ 有关的信号可简写成

$$I(\tau)\propto S_1(\tau)+S_2(\tau),\qquad(15)$$

式中

$$S_1(\tau)=|\varepsilon|^2\int_{-\infty}^{+\infty}\mathrm{d}\omega'\int_{-\infty}^{+\infty}\mathrm{d}\omega\frac{\exp[\mathrm{i}(\omega+\omega')\tau]}{4\gamma_2^2+(\Delta+\omega+\omega')^2}\frac{1}{\gamma_1+\mathrm{i}(\omega'-\Delta)}\frac{1}{\gamma_1-\mathrm{i}(\omega-\Delta)},\qquad(16a)$$

$$S_2(\tau)=|\varepsilon|^2\int_{-\infty}^{+\infty}\mathrm{d}\omega'\int_{-\infty}^{+\infty}\mathrm{d}\omega\frac{\exp[\mathrm{i}(\omega+\omega')\tau]}{4\gamma_2^2+(\Delta+\omega+\omega')^2}\frac{1}{\gamma_1^2+(\omega'-\Delta)^2},\qquad(16b)$$

利用复变函数知识可以证明：

$$S_1(\tau)=0,\qquad(17a)$$

$$S_2(\tau)=\frac{\pi^2|\varepsilon|^2}{\gamma_2(2\gamma_2-\gamma_1)}\exp(\mathrm{i}\Delta\tau)\times\exp(-2\gamma_2\tau),\qquad(17b)$$

进而，共轭波信号强度可写成

$$I(\tau)\propto\frac{\pi^2|\varepsilon|^2}{\gamma_2(2\gamma_2-\gamma_1)}\exp(\mathrm{i}\Delta)\exp(-2\gamma_2\tau),\qquad(18)$$

式中因子 $\exp(\mathrm{i}\Delta\tau)$ 是由于探测光与抽运光频率不同引起的的载流子脉动，因子 $\exp(-2\gamma_2\tau)$ 是与载流子-载流子散射、载流子-纵波光学声子和热库扰动相关的衰减。由(18)式不难看出：用非简并时延四波混合方法不仅能从信号强度随时间延迟衰减确定半导体光放大器的响应时间，而且能观测到载流子脉动。更重要的是，由于共轭光与抽运光和探测光频率不同，因而，可方便地利用全光通信器件对这种时间相关技术进行设计使半导体光放大器超快过程研究设备微型化。

4 实验设置

在半导体光放大器中，其非简并时延四波混合实验设置可考虑为如图 3 所示的结构，其抽运光源为半导体发光二极管(LED)，探测光源为激光二极管(LD)。从 LED 发出的光经掺铒光纤放大器(EDFA)，由耦合器 C_1 分为两束，一束只经多模光

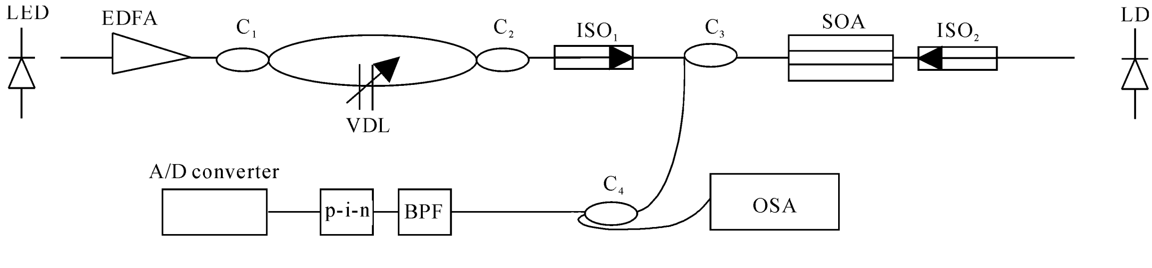

Fig. 3 Schematic of experimental setup for measurement of the carrier pulsation and dephasing time in the SOA. LED: light emitting diode; LD: laser diode; EDFA: erbium-doped fiber amplifier; C: coupler; VDL: variable delayed line; ISO-isolator; SOA: semiconductor optical amplifier; BPF: bandpass filter; OSA: optical spectrum analyzer; p-i-n: photodetecter; A/D-converter: analog/digital converter

纤，另一束经可变延迟线(VDL)再由耦合器 C_2 合为一束经隔离器 ISO_1 进入半导体光放大器。其探测光经隔离器 ISO_2 进入半导体光放大器从而构成图 2 所示的相共轭时延四波混合。共轭波信号经光电探测器转换成电信号。继而，用模数转换器进行数据处理。实验时，通过改变延迟线观察信号强度随时间延迟的变化，就可观测载流子的脉动情况，经与(18)式进行拟合，可确定半导体光放大器的退相速率。

结论 对半导体光放大器宽带二能级模型进行了非简并时延四波混合理论研究，得出了合乎全光通信器件设计要求的实验公式，进而，提出了利用全光通信器件构成时延四波混合用以观测半导体光放大器载流子脉动、响应时间(退相时间)的新方案。这有利于选取与半导体光放大器相匹配的抽运与探测光波长，且可使时延四波混合实验微型化。

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