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LD抽运被动调 Q Nd: YAG/$GdVO_4$ 内腔式喇曼激光器

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摘要: 为了研究LD抽运的被动调 Q Nd: YAG/$GdVO_4$ 内腔式喇曼激光器的输出特性, 采用Nd: YAG作为激光介质, $GdVO_4$ 晶体作为喇曼介质, 分别用两块不同初始透过率的 Cr^{4+}: YAG晶体, 得到并比较了采用不同初始透过率的 Cr^{4+}: YAG晶体时被动调 Q 喇曼激光器的性能。测量了平均输出功率、脉冲宽度和脉冲重复率随抽运功率的变化关系。当 Cr^{4+}: YAG的初始透过率为91%、输入功率是5.2W时, 得到的喇曼光的最高功率为150.6mW, 相应的转换效率为2.9%。结果表明, 通过数值求解基频光和喇曼光空间分布的速率方程并应用到被动调 Q 内腔式喇曼激光器, 获得的理论结果与实验结果大致相符。

关键词: 激光器; 固体激光器; 喇曼激光器; 受激喇曼散射; $GdVO_4$ 晶体; 被动调 Q
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LD pumped passively Q-switched Nd: YAG/$GdVO_4$ intracavity Raman laser

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Abstract: In order to study of outpnt characteristics of a laser diode pnmped passively Q-switched Nd: YAG/$GdVO_4$ intracavity Raman laser, taking Nd: YAG as the gain crystal, $GdVO_4$ as the Raman medium, and two Cr^{4+}: YAG crystals with different initial transmissions as the saturable absorber respectively, the passively Q-switched operation of the Nd: YAG/$GdVO_4$ Raman laser at 1174nm was investigated and compared. The average power, pulse energy, pulse width and pulse repletion rate of diode pumped passively Q-switched Nd: $GdVO_4$ self-Raman laser at 1174nm with respect to the injected pump power were measured. The obtained maximum output average power was 150.6mW with respect to injected power of 5.2W and the corresponding conversion efficiency was 2.9% in the case of the initial transmission of 91%. The theoretical results were obtained according to the rate equations, in which the Gaussian distribution of the intracavity photon density of the fundamental and Raman laser and the initial population inversion density were taken into account. The obtained theoretical results were in agreement with the experimental results on the whole.

Key words: lasers; solid-state laser; Raman laser; stimnlated Raman scattering; $GdVO_4$ crystal; passive Q-switching

引 言

晶体中的受激喇曼散射(stimulated Raman scattering, SRS)是扩展现有激光光谱范围的一种有效的频率转换的方法。随着一些喇曼晶体的广泛研究, 例如 $Ba(NO_3)_2$[1], $KGd(WO_4)_2$[2], $SrWO_4$[3-4], $GdVO_4$ 和 YVO_4[5-13]等, 以LD作为抽运源的全固态喇曼激光器结构紧凑、效率高、性能稳定, 因而成为近几年来的研究热点[14-17]。

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被动调 Q 内腔式喇曼激光器具有许多优点, 如阈值低、体积小、脉宽窄、峰值功率高以及脉冲重复率可以通过饱和吸收体控制等等, 所以受到广泛关注。作者对LD抽运被动调 Q Nd: YAG/$GdVO_4$ 内腔式喇曼激光器的实验特性进行了详细研究。通过利用两块不同初始透过率的 Cr^{4+}: YAG晶体, 分别测量了平均输出功率、脉冲宽度和脉冲重复率随抽运功率的变化。研究和比较了被动调 Q Nd: YAG/$GdVO_4$ 内腔式喇曼激光器的输出特性。通过数值求解基频光和喇曼光空间分布的速率方程, 并应用到被动调 Q Nd: YAG/$GdVO_4$ 内腔式喇曼激光器。获得的理论结果与实验结果大致相符。

1 实验装置与结果

LD抽运的被动调 Q Nd: YAG/$GdVO_4$ 喇曼激光器

如图1所示,抽运源与参考文献[4]中的一样。输入

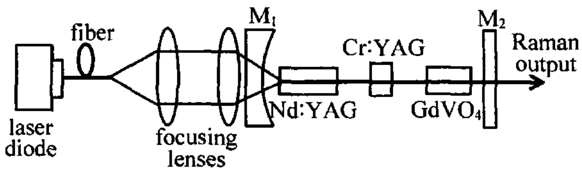

Fig. 1　Experimental arrangement of the diode-pumped passively Q-switched Nd: YAG/$GdVO_4$ Raman laser

镜M_1是曲率为1000mm的凹镜,对1064nm基频光和1174nm喇曼光高反($R>99.7\%$),对808nm抽运光高透($T>96\%$)。输出耦合镜为两片平面镜,其中一片对1174nm喇曼光的反射率为93%,另一片对1174nm喇曼光的反射率为75%,对1064nm光的反射率都为99.8%。激光晶体Nd:YAG的掺Nd的原子数分数为0.01,晶体尺寸为∅4mm×5mm。实验采用尺寸为3mm×3mm×15mm的$GdVO_4$晶体,Nd:YAG和$GdVO_4$晶体的两个端面镀有对1000nm~1200nm的抗反膜。实验中采用两片Cr^{4+}:YAG晶体,初始透过率T_0分别为84%和91%,被动调Q晶体长度为1mm,前后端面镀有1.0m~1.35m波段的增透膜。激光谐振腔长度为60mm。

图2~图5中给出了被动调Q Nd:YAG/$GdVO_4$喇曼激光器的输出特性与抽运功率之间的变化关系。其中,图2a~图5a中是使用输出镜反射率为93%时的平均输出功率与抽运功率的变化关系,图2b~图5b是使用输出镜反射率为75%时的平均输出功率与抽运功率的变化关系。图中,实心正方形代表的是Cr^{4+}:YAG的初始透过率为84%时的实验值,实心三

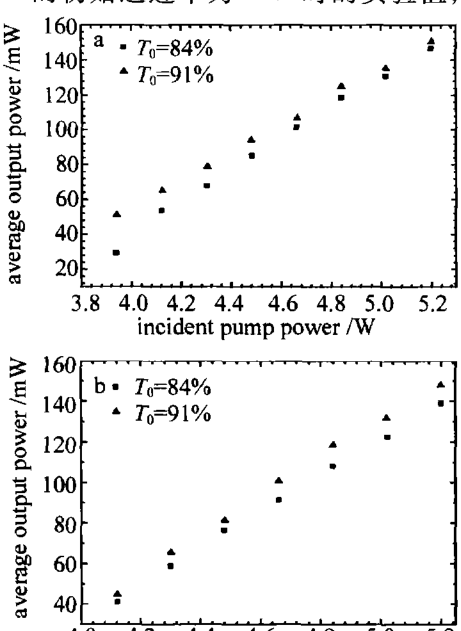

Fig. 2　Average output power at 1174nm with respect to the injected pump power at 808nm for $T_0=84\%$ and $T_0=91\%$, respectively
a—$R=93\%$　b—$R=75\%$

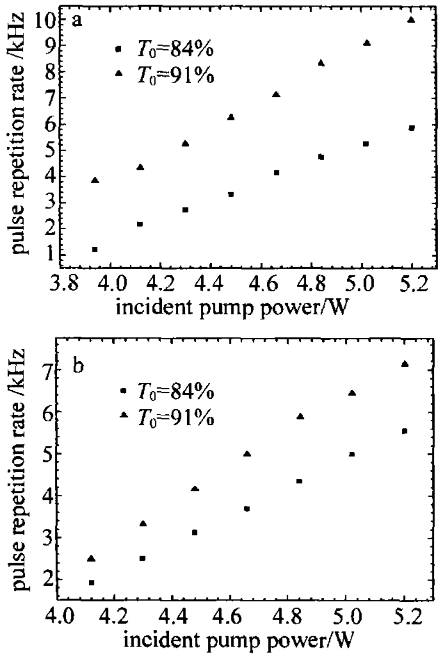

Fig. 3　Pulse repetition rate at 1174nm with respect to the injected pump power at 808nm for $T_0=84\%$ and $T_0=91\%$, respectively
a—$R=93\%$　b—$R=75\%$

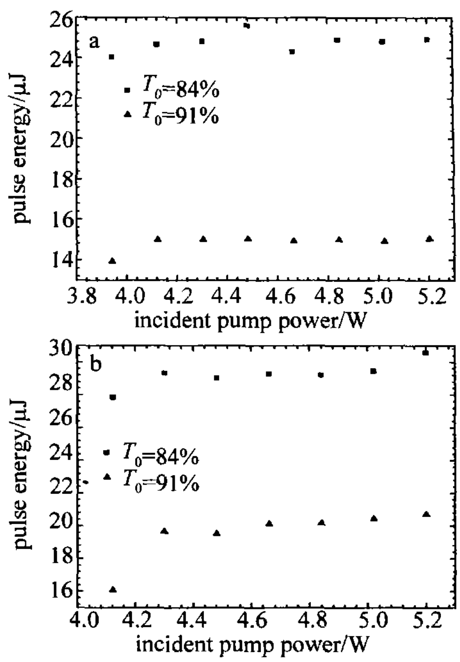

Fig. 4　Pulse energy at 1174nm with respect to the injected pump power for $T_0=84\%$ and $T_0=91\%$, respectively
a—$R=93\%$　b—$R=75\%$

角形代表的是Cr^{4+}:YAG的初始透过率为91%时的实验值。由图2看出,平均输出功率随着抽运功率的增加而增加,当抽运功率相同时,增加饱和吸收体的初始透过率,平均输出功率会随着增加。使用两种输出镜时喇曼光的平均输出功率相差不大。

喇曼光的脉冲重复率由输出镜的反射率R,Cr^{4+}:YAG的小信号透过率T_0和抽运功率共同确定。图3中给出了R和T_0取不同值时,脉冲重复率随着抽运功率的变化情况。随着抽运功率的增加,脉冲重复

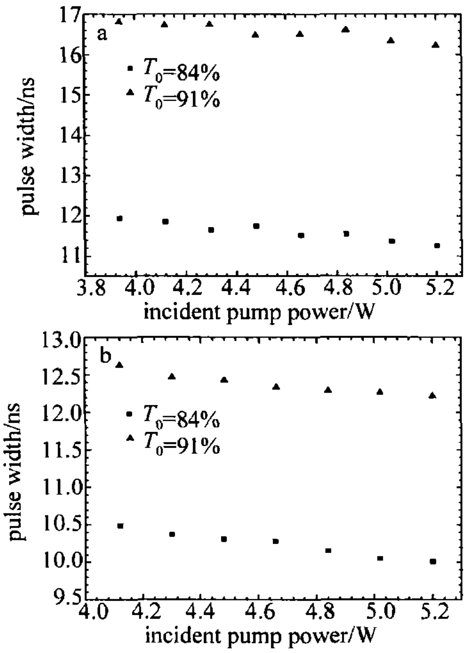

Fig. 5 Pulse width at 1174nm with respect to the injected pump power at 808nm for T_0 = 84% and T_0 = 91%, respectively
a—R = 93% b—R = 75%

率增加。在相同的抽运功率下,随着 Cr^{4+}: YAG 的小信号透过率 T_0 增加,脉冲重复率也会增加。

单个调 Q 脉冲的能量和宽度主要由输出镜的反射率 R 和 Cr^{4+}: YAG 的小信号透过率 T_0 确定,抽运功率也略有影响。图4 和图5 中分别给出 R 和 T_0 取不同值时,单个调 Q 脉冲的能量和宽度随抽运功率的变化关系。由图4 和图5 可知,Cr^{4+}: YAG 的小信号透过率 T_0 越小,单个脉冲的能量就越大,脉冲宽度就越小。对于固定的 R 和 T_0,单个脉冲的能量随抽运功率的增大而略有增大,脉冲宽度随抽运功率的增大而略有减小。

2 理论分析

在被动调 Q 激光器的速率方程中加入描述受激喇曼散射效应的一项和1阶斯托克斯光的微分方程就可以得到被动调 Q 喇曼激光器的速率方程。对参考文献[18]中的速率方程进行修改可以得到考虑空间高斯分布的被动调 Q 内腔式喇曼激光器的速率方程:

$$\int_0^\infty \frac{\mathrm{d}\phi_1(r,t)}{\mathrm{d}t}2\pi r\mathrm{d}r = \int_0^\infty \frac{2\phi_1(r,t)}{t_{\mathrm{rt}}}\{\sigma n(r,t)l - \sigma_{\mathrm{g}}n_{\mathrm{s}}(r,t)l_{\mathrm{s}} - \sigma_{\mathrm{t}}[n_{\mathrm{s0}} - n_{\mathrm{s}}(r,t)]/l_{\mathrm{s}}\} - \int_0^\infty \frac{2\phi_1(r,t)}{t_{\mathrm{rt}}}gh\nu_{\mathrm{R}}c\phi_{\mathrm{R}}(r,t)l_{\mathrm{R}}2\pi r\mathrm{d}r - \int_0^\infty \frac{\phi_1(r,t)}{t_{\mathrm{rt}}}\left[\ln\left(\frac{1}{R_1}\right) + L\right]2\pi r\mathrm{d}r \tag{1}$$

$$\int_0^\infty \frac{\mathrm{d}\phi_{\mathrm{R}}(r,t)}{\mathrm{d}t}2\pi r\mathrm{d}r = \int_0^\infty \frac{2\phi_{\mathrm{R}}(r,t)}{t_{\mathrm{rt}}}gh\nu_{\mathrm{R}}c\phi_1(r,t)l_{\mathrm{R}}2\pi r\mathrm{d}r - \int_0^\infty \frac{2\phi_{\mathrm{R}}(r,t)}{t_{\mathrm{rt}}}\{R_{\mathrm{ratio}}\sigma_{\mathrm{g}}n_{\mathrm{s}}(r,t)l_{\mathrm{s}} + R_{\mathrm{ratio}}\sigma_{\mathrm{e}}[n_{\mathrm{s0}} - n_{\mathrm{s}}(r,t)]l_{\mathrm{s}}\}2\pi r\mathrm{d}r - \int_0^\infty \frac{\varphi_{\mathrm{R}}(r,t)}{t_{\mathrm{rt}}}\left[\ln\left(\frac{1}{R_{\mathrm{R}}}\right) + L\right]2\pi r\mathrm{d}r + k_{\mathrm{sp}}\int_0^\infty \phi_1(r,t)2\pi r\mathrm{d}r \tag{2}$$

$$\frac{\mathrm{d}n(r,t)}{\mathrm{d}t} = -\gamma\sigma c\phi_1(r,t)n(r,t) - \frac{n}{t_{\mathrm{sp}}} \tag{3}$$

$$\frac{\mathrm{d}n_{\mathrm{s}}(r,t)}{\mathrm{d}t} = -\frac{S_1}{S_{\mathrm{s}}}\sigma_{\mathrm{g}}c\phi_1(r,t)n_{\mathrm{s}}(r,t) - R_{\mathrm{ratio}}\sigma_{\mathrm{g}}c\phi_{\mathrm{R}}(r,t)n_{\mathrm{s}}(r,t) \tag{4}$$

式中,r 为径向坐标,$n(r,t)$ 是反转粒子数密度,$n_{\mathrm{s}}(r,t)$ 和 n_{s0} 分别是饱和吸收体基态和总的粒子数密度,$\phi_1(r,t)$ 和 $\phi_{\mathrm{R}}(r,t)$ 分别是基频光和喇曼光的光子数密度,$t_{\mathrm{rt}} = 2l_{\mathrm{c}}/c$ 是光在腔内的往返时间,l_{s} 和 l_{R} 分别是饱和吸收体和喇曼晶体的长度,l_{c} 是腔的光学长度,c 是真空中的光速,$h\nu_{\mathrm{R}}$ 是喇曼激光的光子能量,R_1 和 R_{R} 分别是输出镜对基频光和喇曼光的反射率,其它的参量和数值见表1。数值求解方程(1)式和(4)式,就可以得到对小信号透过率分别为84%和91%的理论结果。表2中给出了不同的实验条件下所得的实验结果与理论结果的比较。其中,实验结果的范围是指抽运功率不同时所得到的范围。由表2可以看出,实验结果与考虑腔内光强光子数密度分布时所得的理论结果非常相近,但是也存在一定的差异。其原因有:(1)更换输出镜和饱和吸收体时调整精度不足够高,人为造成一些误差;(2)计算理论结果所用的参量不一定完全符合实际情况;(3)抽运光束并不是严格的高斯分布,而在理论计算中是把初始反转粒子数密度按高斯分布处理。

被动调 Q Nd: YAG/$GdVO_4$ 喇曼激光器的输出光谱通过 YOKOGAWA AQ-6317C 光谱分析仪来测量。实验中基频光的中心波长为1064.1nm,基频光与喇曼光的频移由 $\omega_{\mathrm{R_1}} = 882\mathrm{cm}^{-1}$, $\omega_{\mathrm{R_2}} = 807\mathrm{cm}^{-1}$ 和 $\omega_{\mathrm{R_3}} = 256\mathrm{cm}^{-1}$ 组成,对应于 $GdVO_4$ 晶体中 ${VO_4}^{3-}$ 离子团的振动模[8],最强的振动模是 $\omega_{\mathrm{R_1}} = 882\mathrm{cm}^{-1}$。在低功率抽运时测得喇曼光的光谱有两条谱线组成,中心波长

Table 1　Parameters used in the calculation

parameter	value
laser stimulated emission cross section σ	$1.2\times10^{-23}m^2$
ground-state absorption cross section of saturable absorber σ_g	$4.3\times10^{-22}m^2$
excited-state absorption cross section of saturable absorber σ_e	$8.2\times10^{-23}m^2$
inversion-reduction factor γ	0.71
ratio of absorption cross sections of saturable absorber at laser and Stokes wavelengths R_{ratio}	0.2
spontaneous-emission lifetime of laser medium t_{sp}	100μs
upper-level lifetime of saturable absorber t_s	4μs
round-trip loss in the cavity L	0.05
raman gain with 1064nm pump g	4.5×10^{-11}m/W
spontaneous Raman-scattering factor k_{sp}	$2\times10^{-10}s^{-1}$
fundamental beam cross-section areas in the laser gain S	$1.2\times10^{-7}m^2$

Table 2　Comparison between the experimental and theoretical results

experimental conditions		$R=93\%$ $T_0=84\%$	$R=93\%$ $T_0=91\%$	$R=75\%$ $T_0=84\%$	$R=75\%$ $T_0=91\%$
pulse energy/μJ	experimental results	24.1~25.6	13.9~15.1	23.2~24.9	19.5~20.7
	theoretical results	23.5	13.6	25.1	18.4
pulse width/ns	experimental results	10~13	16~18	10~13	11~13
	theoretical results	9.6	17.4	10.2	11.4

分别为1164.2nm和1174.5nm,对应 $GdVO_4$ 晶体的频移分别为 $882cm^{-1}$ 和 $807cm^{-1}$。没有发现频移为 $256cm^{-1}$ 的喇曼光。随着抽运功率的增加,由于 $GdVO_4$ 晶体中 VO_4^{3-} 最强的振动模 $\omega_{R_1}=882cm^{-1}$,中心波长为1164.2nm的喇曼光不满足谐振条件便逐渐消失,只有中心波长为1174.5nm的喇曼光,所以,在上面的实验结果中所指的是波长为1174.5nm喇曼光。图6中给出了基频光的光谱图和频移为 $807cm^{-1}$ 的喇曼光的光谱图,图7是频移为 $882cm^{-1}$ 的喇曼光的光谱图

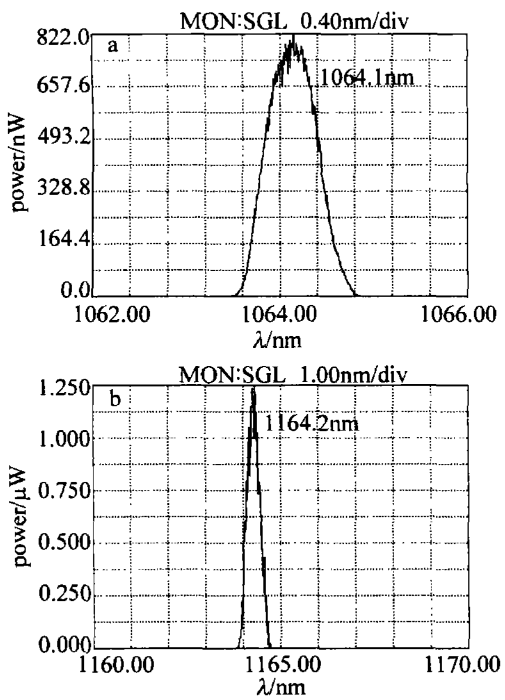

Fig. 6　Output spectra of the intracavity Raman laser
a—fundamental laser　b—Raman laser

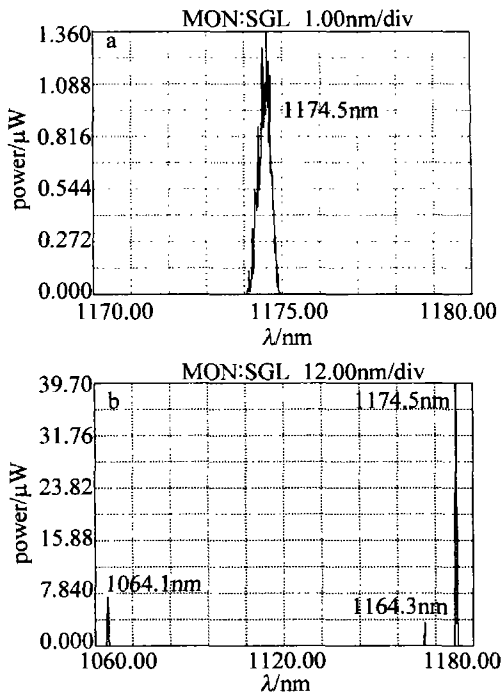

Fig. 7　Output spectra of the intracavity Raman laser
a—Raman lawer　b—fumdamental and Raman lines

和基频光、喇曼光的整体光谱图。主动调 Q 和被动调 Q 自喇曼激光器的输出光谱中没有测量到频移为 $807cm^{-1}$ 和 $882cm^{-1}$ 的喇曼光。

3 结　论

利用Nd: YGA为激光晶体,$GdVO_4$ 为喇曼晶体,Cr^{4+}: YAG为饱和吸收体,实现了被动调 Q Nd: YGA/

$GdVO_4$ 内腔式喇曼激光器的运转。通过分别利用两块不同初始透过率的饱和吸收体，详细研究和比较了被动调 Q Nd: YGA/$GdVO_4$ 内腔式喇曼激光器的输出特性包括平均输出功率、脉冲能量、脉冲宽度和脉冲重复率。通过数值求解考虑空间分布的速率方程，得到的理论结果与实验结果大致相符。

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