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高功率自由空间拉曼放大技术研究进展 (特邀)

白振旭[1,2], 郝　鑫[1,2], 郑　浩[1,2], 陈　晖[1,2], 齐瑶瑶[1,2], 丁　洁[1,2], 颜秉政[1,2],
崔　璨[1,2], 王雨雷[1,2*], 吕志伟[1,2*]

(1. 河北工业大学 先进激光技术研究中心，天津 300401；
2. 河北省先进激光技术与装备重点实验室，天津 300401)

摘　要：高功率特殊波段激光在钠信标、激光测距、激光雷达、自由空间通信等领域具有重要的应用价值。目前，基于受激拉曼散射 (stimulated Raman scattering, SRS) 的拉曼激光器及放大器已经被证实为拓展激光波段和功率的有效途径。不同于基于粒子数反转激光器在产生和放大过程中需匹配激光增益介质固有的吸收和发射谱，SRS 过程理论上能够在其拉曼增益介质透过光谱的全范围内工作，故只需要相互作用光束的频率差满足拉曼增益介质的固有频移，便可实现光束之间的能量直接转移。因此，拉曼放大技术能够利用常规波段的泵浦光对特殊波段的种子光进行放大，从而实现高功率、大能量、高光束质量的特殊波段激光输出。该方法具备波长选择灵活、结构简单、功率拓展性强等优点，近年来已经在钠信标光源等领域得到了应用。文中综述了高功率自由空间拉曼放大技术的主要原理、特性和研究进展，并对其发展趋势和应用前景进行了展望。

关键词：受激拉曼散射；　激光；　放大器；　脉冲；　组束
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0　引　言

自 1960 年世界上第一台激光器——红宝石激光器诞生以来，人们从未停止对激光技术的探索。60 多年以来，新技术、新材料和新工艺的涌现推动着激光器及激光产业不断创新，并带动了前沿科学、信息通信、医疗、制造和国防安全等领域的快速发展[1−5]。其中，高功率高亮度激光作为激光技术发展的重要方向，已成为全球各大科技和军事强国争先研发的对象，这一趋势不仅推动了高功率激光的进步，也促进了许多光学相关学科的发展[6−9]。

为了实现高功率的激光输出，人们提出了激光振荡器直接辐射、激光放大器以及激光组束等方法，如图 1 所示。广义上的“振荡器”包括以粒子数反转激光工作物质和非线性光学材料等作为增益介质的光学谐振腔，其具有结构简单、设计灵活等优点，可以针对不同的应用场景设计不同的腔型或调制方式，从而达到目标需求[10−17]。但是，受到泵浦光功率、增益介质特性、热效应等因素影响，单一激光振荡器输出的功率在实际应用中存在一定的限制。为了进一步提高激光功率，可以采用激光放大技术对已有的激光进行功率放大[18−23]。激光放大技术通常以粒子数反转增益介质或非线性光学增益介质等材料作为工作物质，通过受激辐射的方式对注入激光信号进行功率放大。激光放大器能够针对不同的注入激光参数进行设计 (如行波放大器、再生放大器等)，因此，结构设计较为灵活，但是其放大的功率极限依旧受到单束激光功率、增益介质尺寸和热效应等因素的限制，且往往需要结合复杂的温度和光束质量控制系统[24−27]。激光组束通常是指通过相位控制、偏振控制、光谱控制或非线性光学放大等手段，将若干束低功率的激光在

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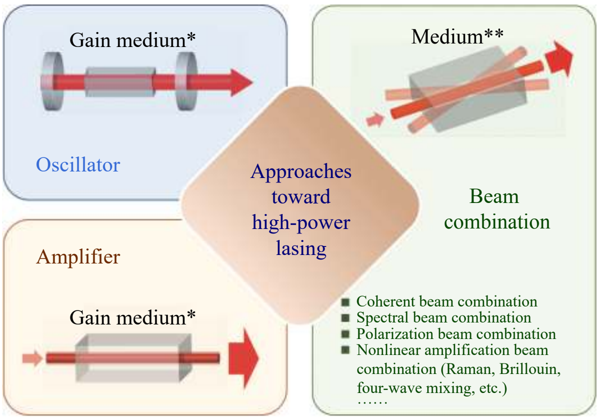
作者简介:白振旭, 男, 教授, 博士, 主要从事高功率激光技术与新型激光器方面的研究。

通讯作者:王雨雷, 男, 教授, 博士, 主要从事高功率固体激光技术与非线性光学方面的研究。
吕志伟, 男, 教授, 博士, 主要从事高功率固体激光技术与非线性光学方面的研究。

空间上合成一束具有更高功率激光光束的技术[28−36]。其特点是能够实现多增益介质和多泵浦源独立运转，具有功率可拓展性强、形式多样、设计灵活等优点，因此在获得高功率高亮度单束激光方面潜力巨大。



* Population inversion based laser gain medium
** Including grating, nonlinear optical materials, phase controller, etc.

图 1 高功率激光的实现途径

Fig.1 Approaches toward high-power lasing

在实现功率缩放的同时，诸多应用领域往往还需要激光器输出特定的波长或波段，以实现光束在部分传输媒介中的透过或吸收。例如：589.159 nm 激光可用于实现钠信标光源；1.5 μm 人眼安全波段的激光可用于激光测距、激光雷达以及自由空间通信等领域；2~5 μm 中红外激光被广泛应用于光谱测量、医疗和遥感等场景；8~12 μm长波红外激光器是实现大气探测、光电对抗等应用的理想光源[37−43]。传统的粒子数反转激光器和放大器由于受到激活粒子有限的发射谱和增益强度影响，往往只能在固定的波长实现激光的直接辐射和放大。而非线性光学的激光频率变换和放大技术能够利用成熟波长的高功率激光提供光子能量，从而突破传统基于粒子数反转的激光器和放大器的功率、波长和增益介质的制约，满足特定应用领域对高功率特殊激光波长的需求[44−49]。其中，基于受激拉曼散射 (stimulated Raman scattering, SRS) 效应的拉曼激光器具有介质选择灵活、频移范围大、波长拓展性强、转换效率高、光束自净化等优点，目前已经实现波长从紫外、可见光到中红外区域，运转方式从连续波、准连续到超短脉冲的高功率高光束质量激光输出[29,50−62]。此外，基于 SRS 的拉曼放大器能够在腔外对满足固定频移关系的激光光束直接进行功率放大，从而大幅度提高特定波长激光的输出功率[63−67]。尤其是自由空间运转的拉曼放大器，其具备不受光束空间排布、横模模式不稳定等条件制约、拉曼增益介质选择更灵活、结构设计更多元化等优点，在实现高功率特定波长激光输出方面具有显著的优势。

文中综述了自由空间拉曼放大技术的工作原理和研究进展，尤其针对最广泛使用的气体和晶体拉曼放大器的结构、特点和研究现状进行了系统的归纳总结，并讨论了其发展过程中面临的困难，期望通过该文为开展拉曼激光器、拉曼放大器和高功率组束激光器研究的人员提供参考。

1 工作原理

SRS 是一种三阶非线性光学效应，其散射过程为非弹性散射。当高功率密度的激光和物质分子发生相互作用时 (具有阈值特性)，物质内部原子或分子振动会使光波产生能量交换，导致激发的散射光频率相较于泵浦光有所差异[68−69]。若散射光的频率低于泵浦光频率，且满足：

$$\omega_S = \omega_P - \omega_V \tag{1}$$

则该散射光称为斯托克斯 (Stokes) 光；若散射光频率高于泵浦光频率且满足：

$$\omega_{AS} = \omega_P + \omega_V \tag{2}$$

则该散射光称为反斯托克斯 (anti-Stokes) 光。公式 (1) 和 (2) 中的 ω_S、ω_{AS}、ω_P、ω_V 分别表示 Stokes 光、anti-Stokes 光、泵浦光和拉曼介质中粒子振动的频率。SRS 的能级跃迁过程可以通过图 2 进行描述。最初，拉曼介质粒子位于基态 (v=0) 能级，在吸收一个泵浦光光子并发射一个 Stokes 光子后，粒子跃迁到激发态 (v=1) 能级上。随后，粒子从激发态 (v=1) 能级退激发到基态 (v=0) 能级，并发射一个能量为$\hbar\omega_V$的声子。粒子从基态 (v=0) 能级到激发态 (v=1) 能级的跃迁可以通过一个中间能级过渡，该能级是非稳能级。

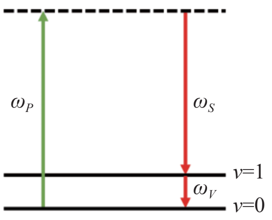


图 2 SRS 能级跃迁示意图

Fig.2 Schematic diagram of SRS energy level transition

SRS 根据泵浦光脉宽 τ_P 与粒子振动弛豫时间 T_2 的长短，可以分为稳态 SRS($\tau_P \gg T$) 和瞬态 SRS($\tau_P \ll T$)。稳态 SRS 过程产生的一阶 Stokes 光功率密度可以表示为：

$$I_S(l_R) = I_S(0)\exp(g_S I_P I_S) \tag{3}$$

式中：I_S 为一阶 Stokes 光功率密度；I_P 为泵浦光功率密度；l_R 为拉曼介质长度；g_S 为一阶 Stokes 光的拉曼增益系数，其表达式为：

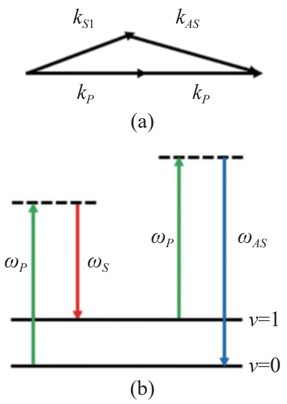
$$g_S = \frac{8\pi c^2 N}{\hbar\omega_P^3 n^2 \Delta\nu_S}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \tag{4}$$

式中：N 为拉曼介质单位体积内的粒子数密度 (cm^{-3})；c 为真空中的光速；$\mathrm{d}\sigma/\mathrm{d}\Omega$ 为自发拉曼散射截面；$\hbar=h/(2\pi)$(h 为普朗克常数)；n 为拉曼介质折射率；$\Delta\nu_S$ 为拉曼谱线宽度。稳态拉曼增益系数与自发拉曼散射截面 $\mathrm{d}\sigma/\mathrm{d}\Omega$ 成正比，与 $\Delta\nu_S$ 成反比。因此，理论上利用窄线宽激光泵浦自发拉曼散射截面的增益介质，可以实现较高的稳态拉曼增益系数。

在满足四波混频 (four-wave mixing, FWM) 相位匹配条件下，SRS 可以产生 anti-Stokes 光，即：

$$\Delta k = 2k_P - k_{S1} - k_{AS} = 0 \tag{5}$$

式中：k_P、k_{S1} 和 k_{AS} 分别为泵浦光、一阶 Stokes 光和一阶 anti-Stokes 光的波矢。在 FWM 过程中，拉曼介质粒子吸收两个泵浦光光子，并放出一个一阶 Stokes 光子和一个一阶 anti-Stokes 光子，在这个过程中拉曼介质内没有产生或消耗声子。图 3(a) 为 FWM 相位匹配示意图，图 3(b) 为反 Stokes 拉曼散射能级跃迁图。



(a)

(b)

图 3 (a) FWM 相位匹配示意图；(b) 反 Stokes 拉曼散射能级跃迁图

Fig.3 (a) Schematic diagram of FWM phase matching; (b) Energy level transition diagram of anti-Stokes Raman scattering

SRS 辐射传输方程可以描述拉曼介质中泵浦光与 Stokes 光的相互作用。1965 年，Shen 和 Bloembergen 根据 SRS 耦合波方程推导出了 SRS 辐射传输方程[70]。2006 年，丁双红考虑高至三阶斯托克斯光及后向 SRS 的情况，在稳态近似条件下建立了适用于外腔拉曼激光器的辐射传输方程[71]。2014 年，王聪建立了适用于拉曼放大器的辐射传输方程，该方程描述了泵浦光参数、Stokes 光参数与拉曼介质参数的变化关系，对于拉曼放大器的设计和优化具有重要的参考价值[67,72]。在泵浦光和 Stokes 种子光沿同一方向单程通过拉曼介质的条件下，拉曼放大器的辐射传输方程可表示为：

$$\frac{n}{c}\frac{\partial I_P(z,t)}{\partial t} + \frac{\partial I_P(z,t)}{\partial z} = -g_P I_P(z,t) I_S(z,t) - \alpha I_P(z,t) \tag{6}$$

$$\frac{n}{c}\frac{\partial I_S(z,t)}{\partial t} + \frac{\partial I_S(z,t)}{\partial z} = g_S I_S(z,t) I_P(z,t) - \alpha I_S(z,t) + K_{SP} I_P(z,t) \tag{7}$$

式中：$I_P(z,t)$、$I_S(z,t)$ 为泵浦光和 Stokes 光在不同空间和时间条件下的功率密度；α 为腔内损耗系数；K_{SP} 为自发拉曼散射系数；g_P 为泵浦光的拉曼增益系数。在拉曼介质长度为 l_R 时，放大后的 Stokes 光在 t 时刻的功率密度为 $I_S(l_R,t)$，忽略损耗和自发拉曼散射，其表达式为：

$$I_S(l_R,t) = \frac{I_0(t)\dfrac{I_S(0,t)}{I_P(0,t)}\exp\left[\dfrac{\omega_S}{\omega_P}g_P I_0(t) l_R\right]}{1 + \dfrac{\omega_P}{\omega_S}\dfrac{I_S(0,t)}{I_P(0,t)}\exp\left[\dfrac{\omega_S}{\omega_P}g_P I_0(t) l_R\right]} \tag{8}$$

$$I_0(t) = I_P(0,t)\left[1 + \frac{\omega_P}{\omega_S}\frac{I_S(0,t)}{I_P(0,t)}\right] \tag{9}$$

参照上述理论模型，笔者可以对外腔拉曼放大器的输出特性进行模拟，从而为自由空间拉曼放大器的设计和参数优化提供理论依据。

目前，自由空间拉曼放大器的常用介质主要包括气体和晶体两种，因此人们通常根据拉曼介质的不同将其分为气体拉曼放大器和晶体拉曼放大器，两者均在高功率特殊波段激光技术领域有着十分重要的贡献。下面对气体拉曼放大器和晶体拉曼放大器的主要特性及研究进展进行介绍。

2 气体拉曼放大器

气体拉曼介质具备拉曼频移大、自聚焦阈值低、光耦合波损耗低、尺寸几乎不受限制等优点，过去在高功率拉曼激光技术领域应用最为广泛。得益于气体拉曼介质的优良特性，气体拉曼放大器在高功率特

殊波段激光技术领域具有重要的研究价值。

2.1 气体共线拉曼放大器

拉曼放大器根据 Stokes 光与泵浦光沿着传输方向在相互作用区域是否存在夹角分为共线和非共线两种结构。共线拉曼放大器通常具备更大的相互作用长度且可以有效避免相位失配，因此能够充分提取泵浦光能量，从而实现高效率大能量的拉曼放大[73−78]。2009 年，Hooper 等人[79] 以 D_2 作为拉曼介质通过共线拉曼放大，得到了单脉冲能量 250 mJ 的1 560 nm 激光输出。2016 年，周冬建等人[80] 以 H_2 为拉曼介质通过共线拉曼放大，得到了单脉冲 44.0 mJ、波长 1.9 μm 的激光输出。此外，共线拉曼放大器还展现了良好的光束净化特性，可以将低光束质量的泵浦光转换为高光束质量的 Stokes 光，从而实现高光束质量的拉曼放大输出。1983 年，Chang 等人[81] 以 H_2 为拉曼介质，基于前向 SRS 放大将畸变的泵浦光转换为发散度略高于衍射极限 1.5 倍的 Stokes 光输出，实验装置如图 4 所示。

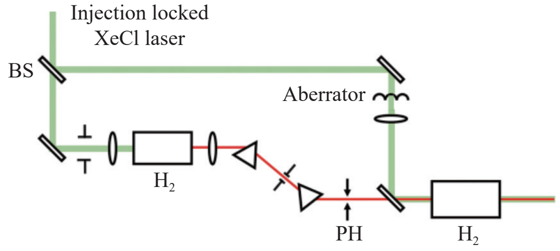


图 4 光束净化装置示意图[81]

Fig.4 Schematic diagram of beam cleaning device [81]

2.2 气体非共线拉曼放大器

单从拉曼增益角度来看，相同注入光参数时，放大器结构宜采用种子光与泵浦光同轴的共线拉曼放大方式以便实现高效率的拉曼转换[82−83]。对应地，非共线拉曼放大方式引起的相互作用长度变短和相位失配将导致拉曼放大的总增益相对有所下降[84−86]。此外，若种子光与泵浦光满足 FWM 相位匹配条件，还会产生二阶 Stokes 光，导致一阶 Stokes 光的转换效率下降。1986 年，Duncan 等人[87] 研究了在不同输入光角度下拉曼放大倍数与泵浦光能量的变化关系。结果显示，在 FWM 相位匹配条件下，拉曼放大倍数随泵浦光能量增大以非指数形式增长，其拉曼放大倍数甚至小于非相位匹配条件下拉曼放大倍数的 10^{-7}。此外，非共线拉曼放大器同样可以实现光束净化。1985 年，继验证了共线放大的光束净化效应后[81]，Chang 等人[88] 通过非共线拉曼放大器将严重畸变 (120× DL) 泵浦光转换为近衍射极限的高光束质量拉曼激光。

当 Stokes 种子光能量较小、泵浦光能量较为充足的条件下，可以采用多通结构使种子光与泵浦光多次相互作用，提高拉曼放大器的转换效率[89−92]。多通拉曼放大器对共线和非共线形式均适用。1984 年，Goldhar 等人[90] 通过 CH_4 气体双通拉曼放大器实现了泵浦光光子提取效率约 75%~85% 的拉曼放大，实验装置如图 5 所示。多通拉曼放大器的输出脉宽可以达到百飞秒量级，Szatmári 等人[91] 和 Glownia 等人[92] 分别通过 ArF 双通拉曼放大器先后得到了脉宽 340 fs 以及脉宽 300 fs 的 193 nm 激光输出。

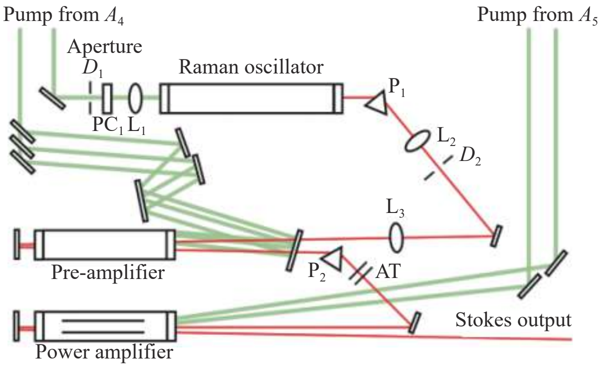


图 5 CH_4 气体双通拉曼放大器示意图[90]

Fig.5 Schematic diagram of CH_4 gas double-pass Raman amplifier [90]

2.3 气体拉曼激光组束

根据光束作用结构的不同，基于拉曼和布里渊放大的激光组束 (两种非线性过程相似) 均可以分为串行激光组束和并行激光组束[28,93−97]。串行和并行拉曼组束的区别在于，串行组束是利用一束 Stokes 光逐级抽取与之相互作用泵浦光的能量，各光束之间可无需进行相位锁定；并行拉曼激光组束利用一束 Stokes 光同时抽取与其相互作用的若干束泵浦光能量，相互作用的光束之间往往需要进行相位锁定。其中，串行拉曼激光组束具有结构设计灵活、功率拓展性强、对光同步要求相对较低等优点，且对 Stokes 光与泵浦光的相互作用形式是否共线没有限制。

1980 年，Jacobs 等人[98] 以 CH_4 为拉曼介质，通过共线拉曼激光组束得到了脉宽 7 ns、波长 268 nm 的后向脉冲输出，实验装置如图 6 所示。1989 年，Mandl 等人[99] 以 H_2 为拉曼介质，利用高度畸变的光束作为泵浦光与近衍射极限的种子光进行共线拉曼激光组

束，得到了单脉冲能量约 0.8 J 的 414 nm 近衍射极限的组束激光。1979 年，Basov 等人[100] 以 H_2 为拉曼介质，通过非共线拉曼激光组束实现了单脉冲能量 360 mJ、脉宽 3 ns 的 1.13 μm 激光输出，实验装置见图 7 (图中，1 atm=1.013×10^5 Pa)。1986 年，Shaw 等人[101−102] 分别以 CH_4 和 H_2 为拉曼介质进行了非共线拉曼激光组束：用 CH_4 为拉曼介质时，实现了单脉冲能量为 8.4 J 的 268 nm 激光组束输出；采用 H_2 为拉曼介质时，实现了单脉冲能量为 5.0 J 的 277 nm 激光组束输出。

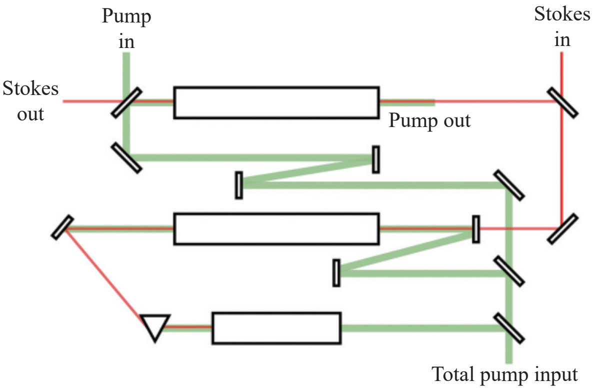


图 6 CH_4 气体拉曼激光组束示意图[98]

Fig.6 Schematic diagram of Raman beam combination in CH_4 gas [98]

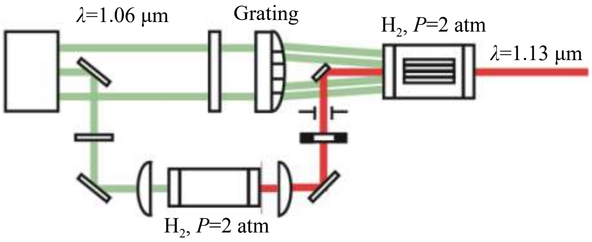


图 7 H_2 气体拉曼激光组束示意图[100]

Fig.7 Schematic diagram of Raman beam combination in H_2 gas [100]

2.4 小 结

气体拉曼放大器具有输出能量高、介质尺寸可拓展性高等优点，表 1 总结了近年来自由空间结构的气体拉曼放大器的参数。目前，自由空间结构的气体拉曼放大器主要应用于短脉宽、高峰值功率、大能量的激光的放大和光束合成，其输出的激光峰值功率已达到兆瓦量级、单脉冲能量达到焦耳量级。但是，气体拉曼放大器也存在气体介质难以保存、增益介质容器体积大、系统集成化较难的问题，且实验中需要对气体的压强等参数进行控制。近年来，基于气体填充空心光纤的拉曼放大器得到广泛的关注，尤其在实现低阈值特定波长转换中具有较为明显的优势[103−104]。

表 1 气体拉曼放大器研究进展

Tab.1 Research progress of Raman amplifier in gas

Year	Raman medium	Structure	Pump wavelength/μm	Stokes wavelength/μm	Output energy/mJ	Pulse duration/ns	Peak power/MW	Ref.
1979	H_2	Beam combination	1.06	1.13	360	3	120	[100]
1980	CH_4	Beam combination	0.248	0.268	-	7	-	[98]
1983	H_2	Collinear amplifier	0.308	0.353	20	50	4	[81]
1986	CH_4/H_2	Beam combination	0.249	0.268/0.277	8400/5000	-	-	[101]
1989	H_2	Beam combination	0.353	0.414	800	-	-	[99]
1996	H_2	Collinear amplifier	0.390	0.465	0.02	0.00035	57.1	[73]
2001	CH_4	Collinear amplifier	0.248	0.268	-	5	-	[83]
2009	D_2	Collinear amplifier	1.064	1.560	250	4	62.5	[79]
2016	H_2	Collinear amplifier	1.06	1.9	44	-	-	[80]

3 晶体拉曼放大器

相较于气体拉曼介质，晶体拉曼介质具有拉曼增益系数高、热导性能好、性能稳定和易于实现小型化等优点。随着晶体制备技术的发展，晶体拉曼介质的品质日益提高，极大推动了晶体拉曼放大器在高功率激光技术领域的应用。

3.1 晶体共线拉曼放大器

2007 年，Raghunathan 等人[105] 实现了首台中红外硅晶体拉曼放大器，输出光波长为 3.39 μm，拉曼增益

高达 12 dB。随后，科研人员们采用 $Ba(NO_3)_2$、YVO_4、KGW、$BaWO_4$、$PbWO_4$、金刚石等晶体拉曼介质陆续进行了实验研究[106−111]，所得输出光脉冲能量主要集中在毫焦量级，单脉冲能量最高为 71.5 mJ，由王聪等人[109] 在 2014 年通过 $BaWO_4$ 拉曼放大器实现，实验装置如图 8 所示。晶体共线拉曼放大器的输出光脉宽集中在纳秒、皮秒等量级，最小输出光脉宽约 6 ps，由 Yakovlev 等人[107] 在 2009 年通过 YVO_4 拉曼放大器实现。2019 年，刘兆军等人[112] 成功将晶体拉曼放大技术应用于钠信标光源领域，结合 $CaWO_4$ 晶体拉曼放大器和倍频技术实现了单脉冲能量 8.2 mJ、线宽 1.3 GHz 的 589.159 nm 钠黄光，光束质量因子小于 1.5。

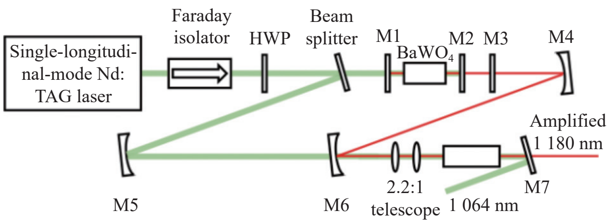


图 8 $BaWO_4$ 前向拉曼放大器示意图[76]

Fig.8 Schematic diagram of $BaWO_4$ forward Raman amplifier[76]

3.2 晶体非共线拉曼放大器

在非共线拉曼放大条件下，拉曼增益因子会随输入光夹角的增加而下降。在 2017 年，McKay 等人[66] 推导了非 FWM 相位匹配条件下有效增益 g_{nc} 与波束偏移 b 的关系，通过公式 $g_{nc}=g_0\exp(-b^2/2)I_0(b^2/2)$ 来表示该变化关系。其中，g_0 是拉曼增益系数，$I_0(x)$ 是第一类零阶修正贝塞耳函数。随着泵浦光与种子光夹角的增大，波束偏移 b 增大，有效增益 g_{nc} 迅速下降。若拉曼放大器中种子光与泵浦光通过 FWM 相互作用，仅在种子光与泵浦光满足相位匹配条件下，拉曼光增益效果最佳。徐洋等人[113] 在 2013 年以 YVO_4 晶体为拉曼介质研究了通过四波混频实现的拉曼放大与输入光夹角的变化关系，实验装置如图 9 所示。他们发现无论是正三阶 Stokes 光，还是反三阶 Stokes 光，只要偏离相位匹配角超过 0.5°，输出光功率密度都会大幅度下降。此外，晶体非共线拉曼放大器的输出脉宽目前主要集中在纳秒、皮秒、百飞秒量级，最小脉宽约 100 fs，由 Grigsby 等人[114] 在 2008 年通过双通结构下的 $Ba(NO_3)_2$ 非共线拉曼放大器实现。

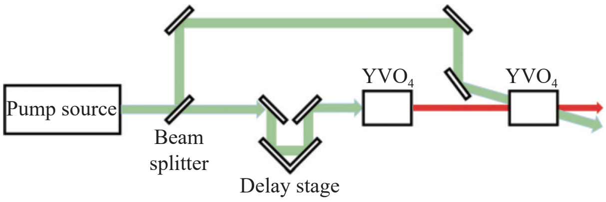


图 9 YVO_4 非共线拉曼放大器示意图[113]

Fig.9 Schematic diagram of YVO_4 non-collinear Raman amplifier[113]

3.3 晶体拉曼激光组束

与气体拉曼激光组束相比，晶体拉曼激光组束减轻了线宽和热负载的约束以及相干光束组合的相位约束。晶体拉曼激光组束目前主要采用串行组束结构和并行组束结构，其中串行组束结构使系统的负载能力得到了大幅提高，实际操作性较强，且可以通过结构优化对系统进行升级。2013 年，Kulagin 等人[115] 实现了以 $Ba(NO_3)_2$ 为拉曼介质的串行拉曼激光组束，通过布里渊和拉曼脉冲压缩产生了脉宽约 30 ps、单脉冲能量 50 mJ 的 1 530 nm 脉冲输出，光束质量接近衍射极限 ($M^2\leqslant1.2$)。在 2015 年，Men 等人[116] 采用 $CaWO_4$ 晶体进行了串行激光组束实验，实现了单脉冲能量 26.7 mJ、峰值功率 5.2 MW 的 1 178 nm 单频激光脉冲输出。在 2019 年，Liu 等人[117] 以 $BaWO_4$ 为拉曼介质实现了串行组束，获得了脉宽 44.1 ns、单脉冲能量 41.0 mJ 的 1 178 nm 单频激光脉冲输出，实验装置如图 10 所示。

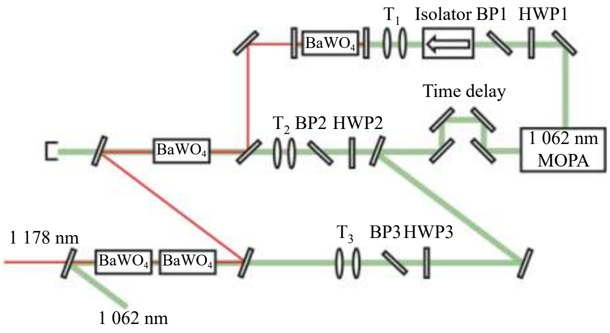


图 10 $BaWO_4$ 晶体拉曼激光组束示意图[117]

Fig.10 Schematic diagram of Raman beam combination in $BaWO_4$ [117]

采用拉曼晶体进行并行激光组束的实验目前较少，但同样是获得高功率特殊波段激光输出的有效方法。在 2017 年，McKay 等人[66] 采用金刚石晶体进行了并行拉曼激光组束实验，得益于金刚石晶体的优良特性[118−121]，实现了峰值功率 8.78 kW 的拉曼激光输出，实验装置如图 11 所示。

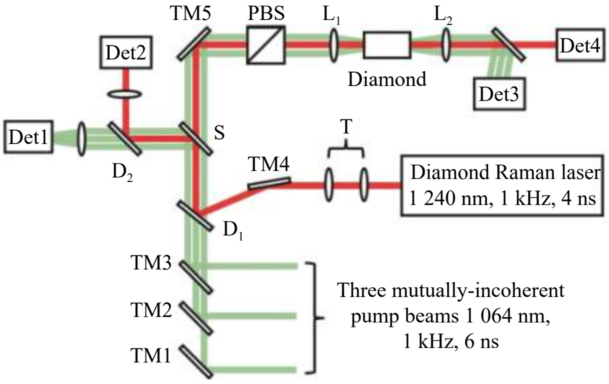


图 11 金刚石晶体拉曼激光组束示意图[66]

Fig.11 Schematic diagram of Raman beam combination in diamond [66]

3.4 小 结

表 2 总结了部分晶体拉曼放大器的实验参数，晶体拉曼放大器的脉宽已经覆盖纳秒、皮秒至飞秒量级，峰值功率已达到 GW 量级、单脉冲能量达到毫焦耳量级。相较于气体拉曼放大器，晶体拉曼放大器的体积小，在实际应用中更具有优势，但是受限于拉曼晶体尺寸等因素其输出能量较低。晶体拉曼放大器的最大单脉冲能量为 71.5 mJ，小于气体拉曼放大器的最大单脉冲能量。未来晶体拉曼放大器发展方向主要在于开发新型拉曼晶体、优化大尺寸晶体制备技术以及优化放大器结构。

表 2 晶体拉曼放大器研究进展

Tab.2 Research progress of crystalline Raman amplifier

Year	Raman medium	Structure	Pump wavelength/ μm	Stokes wavelength/ μm	Output energy/ mJ	Pulse duration/ns	Peak power/MW	Ref.
2008	$Ba(NO_3)_2$	Collinear amplifier	1.064	1.197	63	-	-	[106]
2008	$Ba(NO_3)_2$	Non-collinear amplifier	0.800	0.873	3	10^{-4}	30 000	[114]
2009	YVO_4	Collinear amplifier	1.064	1.174	3×10^{-3}	6×10^{-3}	0.5	[107]
2013	$Ba(NO_3)_2$	Serial laser beam combination	1.319	1.530	50	3×10^{-2}	1 667	[115]
2014	$BaWO_4$	Collinear amplifier	1.064	1.180	71.5	17	4.2	[109]
2014	$PbWO_4$	Collinear amplifier	1.064	1.178	11	-	-	[110]
2015	$CaWO_4$	Serial laser beam combination	1.064	1.178	26.7	2.9	9.2	[116]
2015	Diamond	Collinear amplifier	1.064	1.240	-	-	0.006 96	[111]
2015	Diamond	Parallel laser beam combination	1.064	1.240	-	-	0.008 78	[66]
2018	$BaWO_4$	Collinear amplifier	1.062	1.178	3.5	-	-	[89]
2019	$BaWO_4$	Serial laser beam combination	1.062	1.178	41.0	44.1	0.93	[117]

4 结 论

文中总结了 SRS 和拉曼放大的基本原理，综述了高功率自由空间拉曼放大技术的研究进展。近年来，自由空间拉曼放大技术在大能量高功率特殊波段激光领域取得了许多优秀的成果，但是其输出能量及功率仍然受到拉曼介质参数、单束激光功率等因素的限制。气体拉曼介质存在体积大、增益低、易出现光学击穿等缺陷，在实际应用中存在局限性。随着晶体制备技术的发展，气体拉曼介质逐渐被拉曼增益系数高、化学性质稳定、导热性高的晶体拉曼介质所取代。但是晶体拉曼介质也存在尺寸小、成本高等缺陷，在一定程度上限制了晶体拉曼放大器的输出功率。为了解决该问题，开发新型的拉曼晶体材料和优化大尺寸晶体制备技术是至关重要的。此外，拉曼放大器同样会受到单束激光功率的限制，为了突破以上限制，可以采用拉曼激光组束技术将多束低功率的激光合成为高功率的 Stokes 光。该技术具备功率拓展性高、形式多样、设计灵活等优点，在高功率高亮度激光方面潜力巨大，是未来的重要发展方向。

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Research progress of high-power free-space Raman amplification technology (*invited*)

Bai Zhenxu[1,2], Hao Xin[1,2], Zheng Hao[1,2], Chen Hui[1,2], Qi Yaoyao[1,2], Ding Jie[1,2], Yan Bingzheng[1,2], Cui Can[1,2], Wang Yulei[1,2*], Lv Zhiwei[1,2*]

(1. Center for Advanced Laser Technology, Hebei University of Technology, Tianjin 300401, China;
2. Hebei Key Laboratory of Advanced Laser Technology and Equipment, Tianjin 300401, China)

Abstract:

Significance Lasers with special wavelengths, high power, and high beam quality have significant applications in the fields such as sodium guide star, laser ranging, and free-space communication. One of the effective approaches to extend the spectral range of lasers is based on stimulated Raman scattering (SRS), which can amplify Stokes beam with a desired wavelength using conventional pump sources. This method can produce high-power and high-quality lasers with special wavelengths, and has advantages such as flexible wavelength selection, simple structure, and strong power scalability. In recent years, SRS-based amplifiers have been applied to generate sodium guide star laser sources, and have potential for further development in other areas. This article reviews the main principles, characteristics, and research progress of high-power free-space Raman amplification technology, and discusses its future trends and application prospects.

Progress Currently, the commonly used gain media for Raman amplifiers include gases and crystals. Gas Raman media have advantages such as a large Raman frequency shift, low self-focusing threshold, low optical coupling wave loss, and almost unlimited size. However, they also have disadvantages such as low gain, large volume, and susceptibility to optical breakdown. Compared to gas Raman media, crystal Raman media have advantages such as high Raman gain coefficient, good thermal conductivity, stable performance, and easy miniaturization. However, there are still bottlenecks in the output power and energy of crystalline Raman amplifiers due to factors such as crystal size and damage threshold. Beam combination based on Raman amplification is also an important way to break through the power bottleneck of a single beam and achieve power scaling. This method has advantages such as simple structure, flexible design, and high expandability, and is expected to be further developed and applied in the field of high-power special wavelength lasers. The parameters of gas Raman amplifiers with free-space structures are summarized (Tab.1). At present, the peak laser power output has reached the megawatt level, and the single pulse energy has reached the joule level. The experimental parameters of some crystal Raman amplifiers are summarized (Tab.2). The pulse width of crystal Raman amplifiers is mainly in the nanosecond, picosecond, and femtosecond levels, with peak power reaching the gigawatt level and single pulse energy reaching the millijoule level.

Conclusions and Prospects In recent decades, Raman amplifiers in free space have made many outstanding achievements in the field of high-power special wavelength lasers. However, the output power of Raman amplifiers is still limited by factors such as the Raman medium and amplifier structure. To overcome these limitations, future developments in Raman amplification technology will focus on developing new Raman media, optimizing the preparation technology of large-size Raman crystals, improving the conversion efficiency of Raman amplifiers, and expanding the beam combination structure of high-power Raman lasers. In the future, Raman amplification technology is expected to achieve even greater results in the field of high-power special wavelength lasers.

Key words: stimulated Raman scattering; laser; amplifier; pulse; beam combination

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