中国激光

4.5 W 中红外 3.1 μm 光纤气体激光器

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摘要 在突破了高功率泵浦激光高效稳定耦合关键技术的基础上，利用～30 W 的窄线宽 1.5 μm 光纤激光放大器泵浦一段～8 m 长、充有 300 Pa 乙炔的空芯光纤，实现了 4.5 W 的 3.1 μm 波段中红外激光输出，这是目前中红外光纤气体激光器的最高输出功率，对应的光光转换效率（相对于泵浦源功率）约为 14%。实验结果表明，光纤气体激光器具备输出高功率中红外激光的潜力。

关键词 激光器；光纤激光；气体激光；空芯光纤；乙炔；中红外激光

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1 引言

光纤气体激光器有效结合了光纤激光器和气体激光器两者的优点，是实现中红外激光输出的一种潜在有效手段。空芯光纤将高能量密度激光约束于纤芯内进行长距离传输，增强了激光与气体的相互作用，降低了气体的出光阈值。合理的微结构设计使得硅基空芯光纤支持中红外激光传输，通过充入不同种类的气体作为增益介质，利用气体分子在 1～2 μm 近红外波段的本征吸收[1]，或者基于气体分子的（级联）受激拉曼散射[2]，可以实现 3～5 μm 中红外波段窄线宽光纤激光输出。2011 年，研究者将乙炔充入空芯光纤，实现了 3.1 μm 波段的中红外激光输出[3]。此后，随着空芯光纤的发展，相关研究不断深入[4-9]，到目前为止，光纤乙炔激光器的最高输出功率仅为 1.2 W[6]。最近，国防科技大学在低气压密封条件下的高功率泵浦激光高效稳定耦合关键技术方面取得了重要进展，使用一段～8 m 长、充有 300 Pa 乙炔的空芯光纤，实现了 4.5 W 的 3.1 μm 波段中红外激光输出，这是目前国内外报道的此类激光器的最高输出功率，总光光转化效率为～14%。

图 1 所示为无谐振腔的单程结构的光纤乙炔气体激光器的实验结构示意图，泵浦源为功率最高可达 50 W 的可调谐窄线宽连续波光纤放大器，调谐波段范围覆盖乙炔气体的吸收谱，其中 SEM 表示扫描电镜。泵浦激光被两块放置于三维平移台上的平凸透镜（L_1，L_2）耦合至空芯光纤（HCF）。空芯光纤的两端密封于连有进/出气管道的气体腔中，利用气体腔可以往空芯光纤中充入气体并控制气压。通过改进气体腔中的光纤密封技术，可将注入到空芯光纤中的激光功率从～10 W 有效提升至～30 W。气体腔装嵌有斜 8°放置的玻璃窗口，以抑制反射回光损坏泵浦源。充入空芯光纤中的乙炔气体吸收泵浦激光后，发生粒子数反转，产生 3.1 μm 信号激光。空芯光纤内的信号激光和残余泵浦激光经输出端气体腔窗口输出，再被一块双色镜分离，由功率计（PM）等探测设备接

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收。图 1 中的插图显示了所用的空芯光纤的横截面形状，该光纤为无节点型反共振空芯光纤。

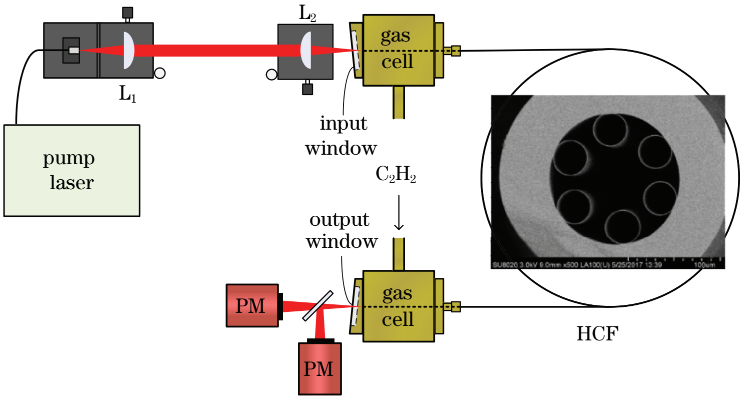

图 1　光纤乙炔气体激光器的实验结构图，插图为空芯光纤的电镜扫描图

Fig. 1　Experimental setup of fiber acetylene gas laser with SEM of hollow core fiber shown in inset

图 2(a)所示为在 1535.39 nm [P(17)吸收线]激光的不同功率泵浦下，空芯光纤充入～300 Pa 乙炔气体后输出的中红外激光光谱，其中包含 P(17)和 R(15)(括号中的数字表示跃迁低能级的转动态量子数，P 和 R 表示高能级与低能级的转动态量子数差值分别为－1 和＋1)两条信号谱线，波长分别为～3106 nm 和～3182 nm。由于系统为单程结构，信号激光为放大的自发辐射，而乙炔分子的吸收谱、发射谱的线宽极小(百 MHz 量级)[1]，因此本文的激光器具备窄线宽的特性。根据乙炔分子的能级结构，两条发射谱线共享同一个上能级，因此存在相互竞争的关系，在不同输出功率下占比不同。在低功率泵浦下，P(17)谱线首先产生，而后随着泵浦功率的增加，R(15)谱线产生，且强度逐渐接近并略微超过 P(17)谱线强度，两条谱线的相对增益关系决定了阈值的差别，增益饱和特性决定了高功率下两者强度相当。

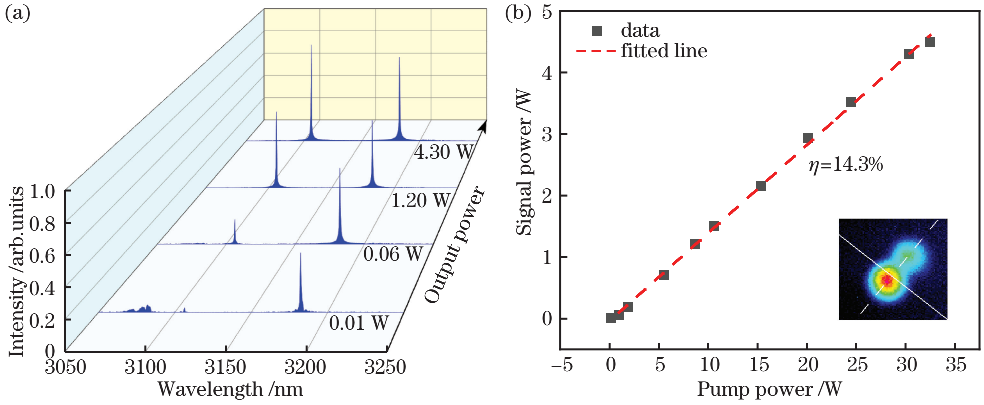

图 2　光纤乙炔气体激光器的输出特性。(a) 300 Pa 气压时不同信号功率下激光器输出光谱；(b) 300 Pa 气压下信号功率随泵浦功率的变化曲线，插图为输出光场

Fig. 2　Output characteristics of fiber acetylene gas laser. (a) Laser output spectra under different signal powers at 300 Pa pressure; (b) signal power versus pump power at 300 Pa pressure with output light field shown in inset

图 2(b)所示为在输出气体腔充入 300 Pa 乙炔的情况下，信号激光的功率随泵浦源功率的变化曲线。本实验的光纤乙炔气体激光器具有较低的泵浦阈值(<0.5 W)，产生的 3.1 μm 中红外激光的最高功率约为 4.5 W，拟合得到的斜率效率(η)约为 14.3%，相应的总光光转化效率为～14%。图 2(b)的插图为输出信号的近场分布，包含一强一弱两个光点，这是因为信号激光通过斜 8°放置的输出端平面窗口后会分成一强一弱的两束激光，该问题可以通过窗口镀膜进行解决。同时，从主光束的光场分布可以看出，空芯光纤输出的中红外激光具有良好的基模特性。

本文利用工作在～1535.39 nm 波长[P(17)吸收线]的可调谐连续波光纤放大器泵浦一段充有乙炔气体的空芯光纤，实现了～3106 nm 和～3182 nm 的 4.5 W 高功率中红外光纤激光输出。实验结果表明，光纤气体激光器具备实现高功率中红外光纤激光输出的潜力，空芯光纤的高功率耦合问题是制

约功率提升的重要因素之一，通过技术改进实现空芯光纤在高功率下的高效密封耦合是实现高功率输出的关键。

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4.5 W 3.1 μm Mid-Infrared Fiber Gas Laser

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Abstract

Objective Fiber gas lasers combine the advantages of fiber lasers and gas lasers, which are potential and effective means to achieve a mid-infrared laser output. The hollow-core fiber (HCF) confines a high-energy-density laser to transmit long distances in the hollow core, which can enhance the laser-gas interaction and reduce the threshold of a gas laser. A reasonable design of microstructures makes the silica-based HCF support mid-infrared laser transmission. By filling different kinds of gases as gain media, a 3–5 μm mid-infrared narrow linewidth fiber laser can be realized in the HCF, based on intrinsic absorption or stimulated Raman scattering of the gas medium. In 2011, acetylene was filled into an HCF for the first time to achieve a mid-infrared laser output in the 3.1 μm band. Since then, with the development of HCFs, related research has continued to deepen. So far, the highest output power of fiber acetylene lasers is only 1.2 W. Recently, the National University of Defense Technology has made an important progress in the key technology of efficient and stable coupling under high pump power and low gas pressure airtight conditions. By improving the sealing technology, we realize a 4.5 W mid-infrared fiber laser at 3.1 μm in an acetylene-filled HCF, corresponding to an optical-to-optical conversion efficiency of 14%, which is the highest output power of such lasers reported at home and abroad.

Methods Figure 1 shows the experimental setup of the single-pass fiber acetylene gas laser without a cavity. The pump source is a tunable narrow linewidth continuous-wave fiber amplifier with a power of up to 50 W, and the tuning band covers the absorption spectrum of acetylene gas. The pump laser is coupled into the HCF through two planoconvex lenses. Both ends of the HCF are hermetically sealed in the gas cells, through which the HCF can be filled into acetylenes and the pressure can be controlled. By improving the sealing technology, the incident power can be effectively increased from ~10 W to ~30 W. The windows placed in the gas cells incline at an angle of 8° to prevent the reflection of back light from destroying the pump source. After the acetylene gas filled in the HCF absorbs the pump laser, the population inversion occurs, and a 3.1 μm signal laser is generated. The generated signal laser and the residual pump laser in the HCF propagate through the output window and are separated by a dichroic mirror. The fiber used in the system is a nodeless anti-resonant HCF, and its cross section is shown in the inset in Fig. 1.

Results and Discussions Pumped by a 1535.39 nm high power fiber amplifier, ~3106 nm [P(17)] and ~3182 nm [R(15)] signal lasers are realized in the HCF filled with ~300 Pa acetylene [Fig. 2(a)]. Due to the single-pass structure without a cavity, the signal laser is amplified spontaneous emission. But because the absorption and emission line widths of acetylene molecules are extremely small (on the order of hundreds of MHz), the fiber acetylene gas laser has the characteristic of narrow line width. The P(17) spectral line is generated first. With the increase of pump power, the intensity of R(15) spectral line gradually approaches and slightly exceeds that of the P(17) spectral line. The relative gain relationship of two spectral lines determines the difference in threshold, and the gain saturation characteristic determines that these two spectral lines are equivalent in intensity at high power. Figure 2(b) plots the curve of the signal laser power versus pump power when the output gas cell is filled with 300 Pa acetylene pressure. The maximum power of ~4.5 W at 3.1 μm is achieved in the HCF filled with 300 Pa acetylene with a slope efficiency of 14.3%. The inclined windows lead to the output laser to be split into two beams, which can be modified by window coating. The original output of the HCF has good fundamental mode characteristics.

Conclusions In summary, we have achieved a 4.5 W mid-infrared laser output at 3.1 μm in an acetylene-filled HCF, corresponding to an optical-to-optical conversion efficiency of 14%, which is the currently the maximum power of a fiber gas laser in the mid-infrared region. The experimental results show that fiber gas lasers have the potential to achieve high-power mid-infrared fiber laser outputs.

Key words lasers; fiber laser; gas laser; hollow-core fiber; acetylene; mid-infrared laser