第 49 卷 第 11 期/2022 年 6 月/中国激光 快 报

中国激光

基于单级 MOPA 结构实现 6 kW 全光纤窄谱激光输出

奚小明[1,2,3]，王蒙[1,2,3]，田鑫[1,2,3]，赵晓帆[1,2,3]，饶斌裕[1,2,3]，王鹏[1,2,3]，杨保来[1,2,3]，张汉伟[1,2,3]，王小林[1,2,3]，王泽锋[1,2,3*]，陈金宝[1,2,3]

[1]国防科技大学前沿交叉学科学院，湖南 长沙 410073；

[2]脉冲功率激光技术国家重点实验室，湖南 长沙 410073；

[3]高能激光技术湖南省重点实验室，湖南 长沙 410073

摘要 高功率窄线宽光纤激光器在非线性频率转换、光谱合成以及相干合成等领域具有广阔的应用前景。本文将自研的窄线宽振荡器作为种子，采用单级主振荡功率放大(MOPA)技术，实现了 6.02 kW 窄谱激光输出。在最高功率时，信号光的中心波长为 1079.26 nm，3 dB 带宽约为 0.36 nm，10 dB 带宽约为 1.47 nm，放大级对应的光-光转换效率约为 85.7%，光束质量 M^2 约为 2.7。据查，这是目前公开报道的窄线宽光纤激光器的单纤最高输出功率。本研究对于高功率窄线宽光纤激光的发展和研究具有重要的指导意义。

关键词 激光器；高功率；窄线宽；主振荡功率放大

中图分类号 O436 **文献标志码** A **DOI**：10.3788/CJL202249.1115001

高功率窄线宽光纤激光器在非线性频率转换、光谱合成以及相干合成等领域具有较大的应用需求。与宽谱光纤激光器相比，窄线宽光纤激光器在功率放大过程中的自相位调制(SPM)、受激拉曼散射(SRS)、受激布里渊散射(SBS)以及模式不稳定(TMI)等非线性效应的阈值更低，所受影响也更大。因此，窄线宽光纤激光器的功率提升更具挑战性。目前，实现窄线宽光纤激光功率放大主要有两种方案：单频相位调制种子放大和单级振荡器种子放大。这两种方案都采用了主振荡功率放大结构，即 MOPA 结构。两者的主要区别在于所用的种子激光器。前者种子激光的时域特性及其在放大过程中的线宽保持特性非常好，并取得了一系列重要突破。2020 年，国防科技大学和中国工程物理研究院分别报道了基于单频相位调制种子的 5 kW 级窄线宽放大器[1-2]。但是其多级放大结构和复杂昂贵的电调制系统导致其性价比和鲁棒性欠佳。由于具有结构简单、对回光不敏感以及鲁棒性强等优点，单级振荡器种子 MOPA 方案近年来受到了广泛关注。近两年来，中国工程物理研究院和清华大学基于该方案分别实现了 3 kW 级保偏和非保偏窄线宽激光输出[3-4]。2021 年，本课题组基于该方案将窄线宽光纤激光功率提升到了 3.44 kW[5]。

在前期实验的基础上，2021 年 9 月，国防科技大学高能激光技术研究所利用单级振荡器种子放大方案实现了 6 kW 全光纤窄谱激光输出。如图 1 所示，实验用放大器包含一个振荡器种子和一个双向泵浦放大级，是典型的单级 MOPA 结构。种子激光器采用自研光纤光栅和纤芯/包层直径为 10 μm/130 μm 的掺镱光纤(YDF)搭建，高反和低反光栅的

收稿日期：2021-12-10；**修回日期**：2022-01-01；**录用日期**：2022-01-24

基金项目：国家自然科学基金面上项目(11974427，12004431)、湖南省自然科学基金杰出青年科学基金(2019JJ20023)、湖南省科技创新人才计划科技创新领军人才项目(2021RC4027)、脉冲功率激光技术国家重点实验室主任基金(SKL2020ZR05，SKL2021ZR01)

通信作者：*zefengwang_nudt@163.com

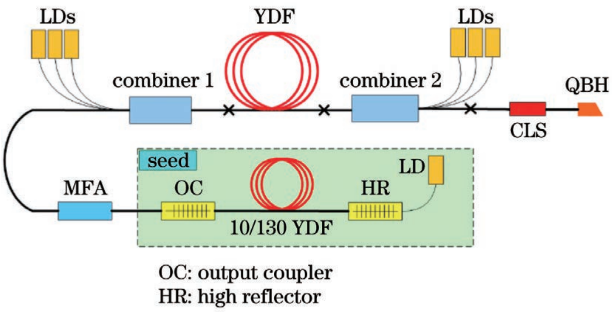

图 1 全光纤窄线宽放大器结构示意图

Fig. 1 A schematic of monolithic fiber amplifier

中心波长均约为 1080 nm，3 dB 带宽分别为 1 nm 和 0.06 nm，反射率分别为 99%和 10%。在工作功率为 20 W 时，种子激光的 3 dB 谱宽为 0.05 nm。种子激光经过模场匹配器（MFA）后注入到放大级中进行放大。放大级采用纤芯/包层直径为 30 μm/400 μm 的大模场双包层 YDF 作为增益介质，纤芯数值孔径 *NA* 约为 0.065，增益光纤长度约为 22 m。中心波长为 981 nm 的稳波长 LD 输出的泵浦光通过前向和后向泵浦/信号合束器注入到 YDF 中。输出激光经过包层光滤除器（CLS）净化后由光纤端帽（QBH）输出，输出光纤的长度（由合束器输出到 QBH）约为 3 m。

实验中，通过优化种子激光的时域特性以及放大级的结构盘绕方式，大大提升了放大器中的 TMI 和 SRS 阈值，最终在泵浦功率约为 7 kW 时实现了最高输出功率为 6.02 kW 的激光输出，放大器对应的光-光转换效率约为 85.7%。从图 2(a)所示的功率曲线图可以看出在输出功率增大过程中光-光转换效率没有出现降低的现象。在最高功率时，信号光的中心波长约为 1079.2 nm，3 dB 线宽约为 0.36 nm，10 dB 线宽约为 1.47 nm，此时拉曼抑制比约为 27 dB。当功率超过 4.4 kW 后，由于模间四波混频，随着功率输出提升，高阶模占比增加，激光器光谱底部出现了较为严重的展宽，但 3 dB 线宽展

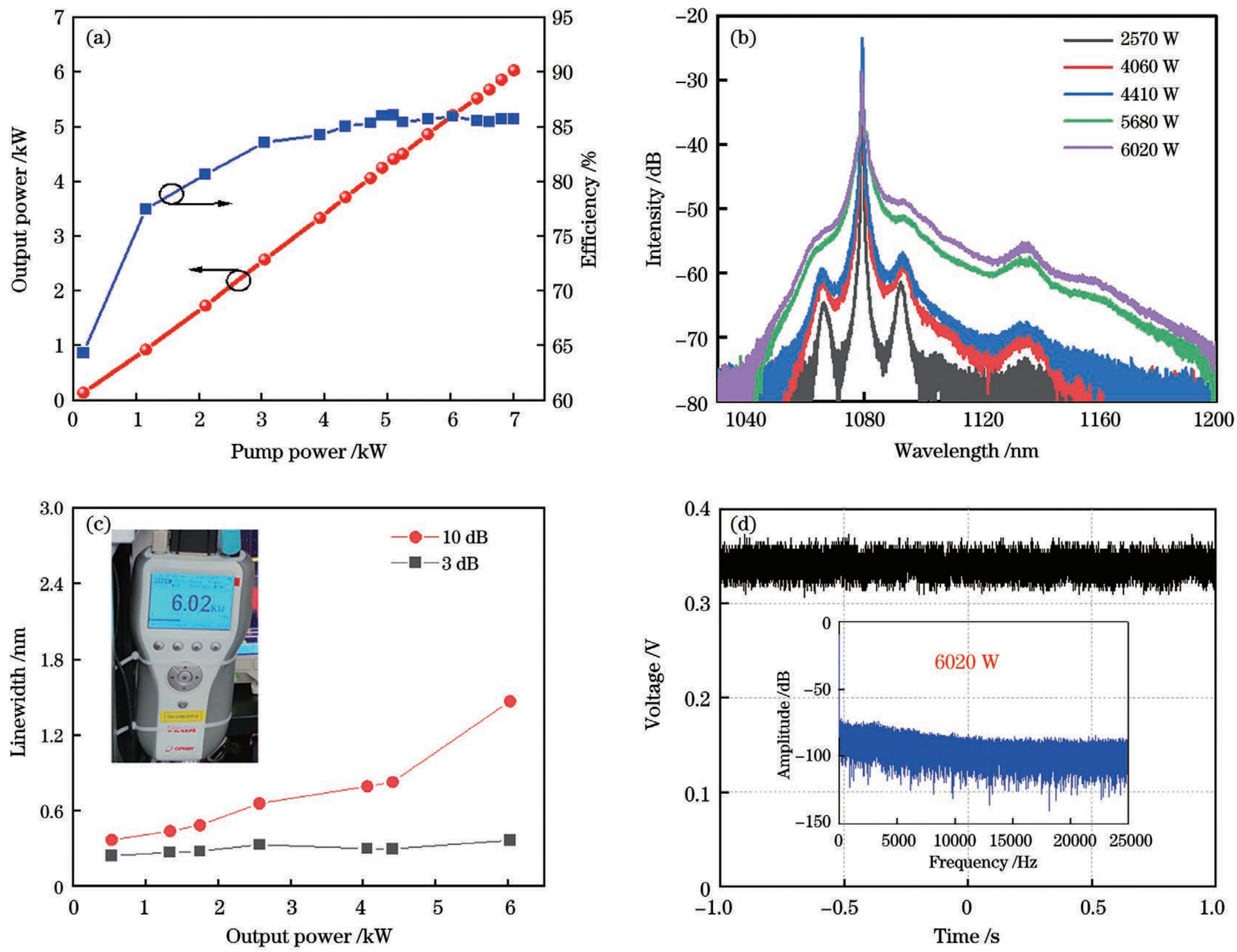

图 2 窄线宽放大器输出激光特性。(a)输出功率和效率；(b)输出光谱；(c)不同功率下的 3 dB 和 10 dB 线宽；(d)时序以及对应的傅里叶频谱

Fig. 2 Laser characteristics of narrow linewidth fiber amplifier. (a) Output power and efficiency; (b) laser spectra; (c) 3 dB and 10 dB linewidths at different powers; (d) temporal signal and corresponding Fourier spectrum

开不明显；此时光束质量也出现了下降，6020 W 功率水平下测得的光束质量 M^2 为 2.7，焦点处的光斑变为环形。通过光电探测器信号观察到了输出激光的波动，表明该放大器功率的进一步提升受限于 TMI。

本文基于单级 MOPA 结构放大器，采取多项非线性效应抑制措施，将窄线宽光纤激光器的输出功率提高到了 6.02 kW 水平。下一步本课题组将继续优化种子激光的时域特性以及放大器的结构，以实现激光器输出功率和光束质量的进一步提升。

参 考 文 献

[1] Ma P F, Xiao H, Liu W, et al. All-fiberized and narrow-linewidth 5 kW power-level fiber amplifier based on a bidirectional pumping configuration[J]. High Power Laser Science and Engineering, 2021, 9: e45.

[2] Huang Z M, Shu Q, Tao R M, et al. >5 kW record high power narrow linewidth laser from traditional step-index monolithic fiber amplifier [J]. IEEE Photonics Technology Letters, 2021, 33(21): 1181-1184.

[3] Wang Y S, Ke W W, Peng W J, et al. 3 kW, 0.2 nm narrow linewidth linearly polarized all-fiber laser based on a compact MOPA structure[J]. Laser Physics Letters, 2020, 17(7): 075101.

[4] Huang Y S, Xiao Q R, Li D, et al. 3 kW narrow linewidth high spectral density continuous wave fiber laser based on fiber Bragg grating [J]. Optics & Laser Technology, 2021, 133: 106538.

[5] Wang M, Xi X, Wang Z, et al. 3.44 kW narrow-linewidth one-stage MOPA fiber lasers [C] // 12th International Conference on Information Optics and Photonics, July 23-26, 2021, Xi'an, China. Shanghai: Chinese Laser Press, 2021: 294.

Record High-Power Narrow-Linewidth Fiber Laser Based on One-Stage Master Oscillator Power Amplification Configuration

Xi Xiaoming[1,2,3], Wang Meng[1,2,3], Tian Xin[1,2,3], Zhao Xiaofan[1,2,3], Rao Binyu[1,2,3], Wang Peng[1,2,3], Yang Baolai[1,2,3], Zhang Hanwei[1,2,3], Wang Xiaolin[1,2,3], Wang Zefeng[1,2,3*], Chen Jinbao[1,2,3]

[1] *College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha* 410073, *Hunan, China*;

[2] *State Key Laboratory of Pulsed Power Laser Technology, Changsha* 410073, *Hunan, China*;

[3] *Hunan Provincial Key Laboratory of High Energy Laser Technology, Changsha* 410073, *Hunan, China*

Abstract

Objective The power scaling of high-power narrow-linewidth fiber lasers has recently received a lot of attention. It is challenging for power scaling in a narrow-linewidth fiber laser since thresholds of nonlinear effects, such as self-phase modulation (SPM), stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS) and transverse mode instability (TMI), are much lower than those in a conventional fiber laser. A narrow-linewidth seed could be boosted using a master oscillator power amplification (MOPA). Two promising seed sources, i.e., phase-modulated single-frequency laser and fiber Bragg grating-based oscillator, are used in the narrow linewidth MOPA, and 3 kW and 5 kW level narrow-linewidth fiber lasers have been reported experimentally based on them, respectively. MOPAs based on the first type of seeds exhibit relatively weaker nonlinear effects and induce smaller spectrum broadening. However, the multistage configuration limits their applications. MOPAs based on the second kind of seeds (i.e., one-stage MOPA) possess a simple and robust structure. Based on experimental and theoretical results, using one-stage MOPA is a promising method for producing high power narrow-linewidth fiber lasers .

Methods The one-stage MOPA system comprises a narrow-linewidth fiber oscillator and bidirectional pumped amplifier. A pair of homemade fiber Bragg gratings (FBGs) and a piece of Yb-doped fiber (YDF) with a core/cladding diameter of 10/130 μm were used to establish the seeds. High reflector (HR) and the output coupler (OC) FBGs are 1.0 and 0.06 nm, respectively. The measured 3 dB bandwidth of the seed is ～0.05 nm at the output power of 20 W. A large-mode-area (LMA) YDF with a mode-filed area of ～420 μm^2 was used in the amplifier. The seed laser

was coupled into the amplifier using a mode-field adapter (MFA) to mitigate the mode-filed mismatching between them. Groups of wavelength-optimized LDs were spliced with the forward and backward combiners and used as pump sources. The unabsorbed cladding light was stripped off using a cladding light stripper. Then the output power, optical spectrum, and beam quality of the laser were measured using a characterization setup.

Results and Discussions A maximum output power of 6.02 kW was achieved at a pump power of 7.0 kW, with the corresponding optical-to-optical efficiency of 85.7%. An evident spectral wing broadening can be observed with the increase of the output power [Figs. 2(b) and (c)]. However, the 3 dB and 10 dB bandwidths of the spectrum increase relatively slow. At the maximum power, the measured 3 dB and 10 dB linewidths of the laser are 0.36 and 1.47 nm, respectively. The Raman suppression ratio is ~27 dB. Because of the large core size of the fiber, the output laser operates in a multimode regime and measured M^2 is ~2.7 at the maximum power.

Conclusions This paper demonstrated a 6.02 kW narrow-linewidth fiber laser based on a one-stage MOPA fiber laser system. At the maximum power, the 3 dB and 10 dB linewidths are 0.36 and 1.47 nm, respectively. The peak signal-to-noise ratio is ~27 dB compared with the Raman Stokes light. The beam quality (M^2 factor) is ~2.7. To the best of our knowledge, this is the highest power of narrow-linewidth fiber lasers that have ever been reported. In the following work, we will continue to optimize the temporal properties of the seed and the structure of the amplifier to further improve the output power and beam quality of the laser.

Key words lasers; high power; narrow linewidth; master oscillator power amplification