中国激光

自研 20 μm/400 μm 掺镱光纤实现 4 kW 高品质激光输出

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摘要 基于自主研制的 20 μm/400 μm 掺镱双包层光纤，搭建了主振荡功率放大器，开展了高功率光纤激光实验，实现了中心波长为 1064 nm、最高功率为 4 kW、斜率效率为 81%、光束质量因子(M^2)为 1.39、拉曼抑制比大于 30 dB 的激光输出。据我们所知，该结果是已公开报道的基于国产 20 μm/400 μm 掺镱双包层光纤实现的最高品质激光输出。

关键词 激光器；光纤激光器；高功率；掺镱光纤；双包层光纤

中图分类号 O436 **文献标志码** A **DOI**：10.3788/CJL221436

光纤激光器具有电光转换效率高、结构紧凑、稳定性好的优势，被广泛应用在工业、国防和科研等领域中，以掺镱光纤作为增益光纤的光纤激光器是其中的研究热点[1-7]。作为光纤激光器的核心组成部分，20 μm/400 μm 双包层掺镱光纤是目前商用高功率光纤激光器中最常用的光纤，与 25 μm/400 μm 光纤相比，具有更低的成本，模式控制也更简单。

国内多家单位开展了 20 μm/400 μm 规格的双包层掺镱光纤的研制[8-10]。其中，2015 年，清华大学使用武汉烽火锐光科技有限公司和中国电子科技集团公司第四十六研究所提供的国产 20 μm/400 μm 掺镱双包层光纤作为增益光纤，实现了 3050 W 和 3092 W 的 1080 nm 激光输出，放大级提取效率分别为 67.3% 和 68.2%[8]。2016 年，中国工程物理研究院激光聚变研究中心用 20 μm/400 μm 双包层掺镱光纤实现了最高激光输出功率为 3034 W、斜率效率为 76.6%、光束质量因子(M^2)为 1.58 的激光输出[10]。最近，通过优化光纤预制棒制备工艺，研制出折射率如图 1 所示的 20 μm/400 μm 双包层掺镱光纤，光纤纤芯直径为 19.5 μm，其中，Δn 为纤芯和内包层的折射率差，NA 为纤芯数值孔径。使用该光纤作为放大级增益介质搭建了主振荡功率放大器，采用反向泵浦方式实现了最高功率为 4 kW 的激光输出，系统斜率效率为 81%，最高功率输出时 M^2 为 1.39。

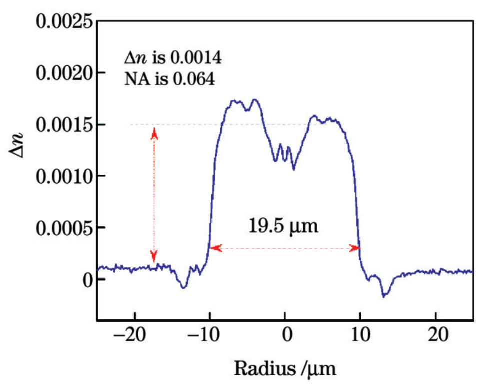

图 1 自研 20 μm/400 μm 掺镱光纤的折射率分布

Fig. 1 Refractive index distribution of homemade 20 μm/400 μm Yb-doped fiber

收稿日期：2022-11-21；**修回日期**：2022-12-26；**录用日期**：2023-01-12；**网络首发日期**：2023-01-22

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图 2 为基于上述自研 20 μm/400 μm 光纤搭建的主振荡功率放大器的结构示意图。其中，种子源的中心波长为 1064 nm，种子光经过模场适配器(MFA)、啁啾倾斜光栅(CTFBG)和包层光剥除器(CPS)后进入放大级。放大级 20 μm/400 μm 光纤长度为 15 m，盘绕直径为 9 cm。系统采用反向泵浦方式，泵浦源由 5 组中心波长为 976 nm 的激光二极管(LD)组成，每组 LD 的最高泵浦功率约为 1030 W，反向集束器的信号臂光纤规格为 25 μm/400 μm。从反向集束器输出的激光经过 CPS 后通过石英端帽(QBH)输出，QBH 输出的种子光功率为 8 W。

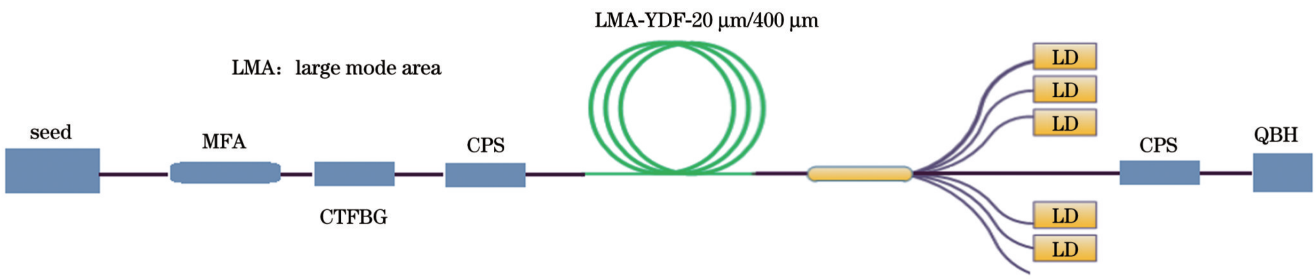

图 2 基于自研 20 μm/400 μm 掺镱光纤的主振荡功率放大器的结构示意图

Fig. 2 Structural diagram of main oscillator power amplifier based on homemade 20 μm/400 μm Yb-doped fiber

图 3 是光纤测试实验结果，其中 M_x^2 为横向光束质量因子，M_y^2 为纵向光束质量因子。从图 3(a)、(b)可以看出，输出激光功率随泵浦光功率呈线性增加，在泵浦光功率为 4999 W 时，实现了 4015 W 的激光输出，此时系统斜率效率(η)为 81%，光束质量因子 M^2 为 1.39。从图 3(c)可以看到，输出激光的中心波长为 1064 nm，在输出功率为 2857 W 时，开始出现微弱的受激拉曼散射(SRS)信号，并随着输出功率的增加而增长。在最高功率下，输出激光的 3 dB 线宽约为 1.3 nm，拉曼抑制比为 31 dB。图 3(d)显示，输出激光时域稳定，未观察到模式不稳定的特征频率成分。

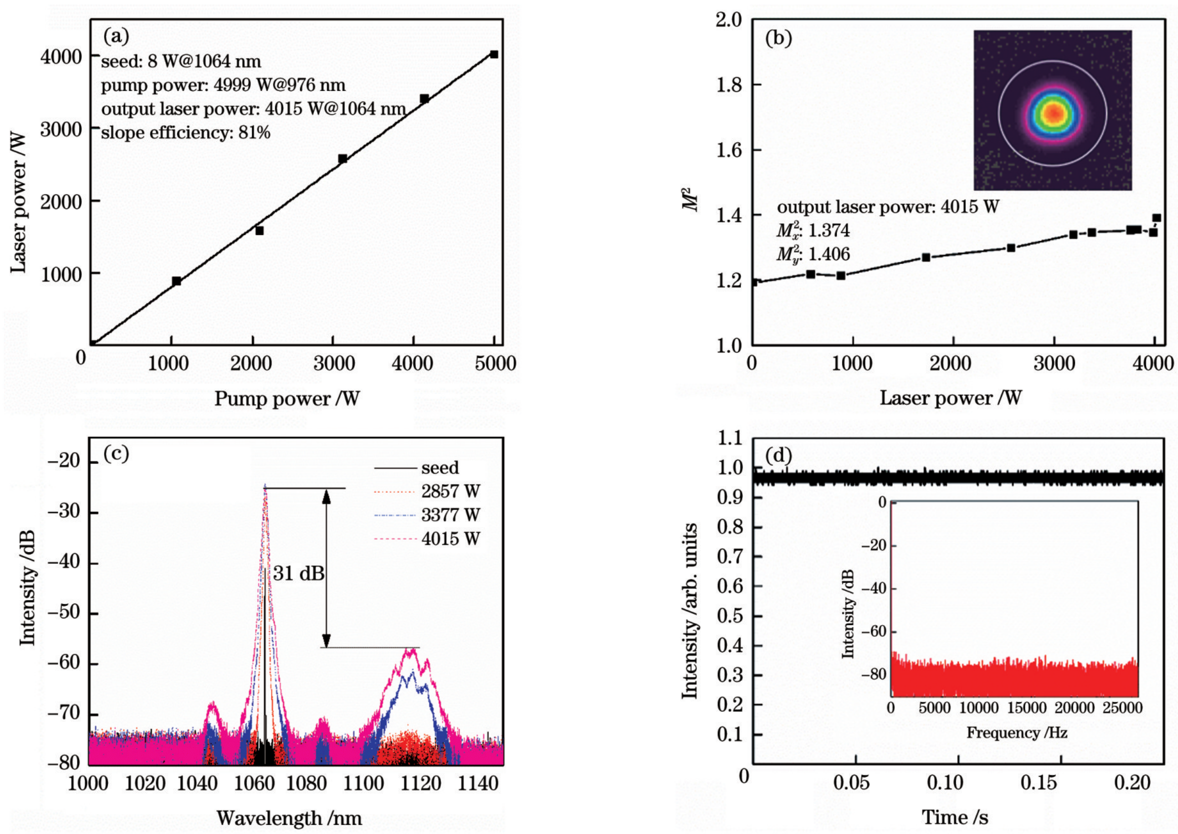

图 3 激光输出特性。(a)输出功率和斜率效率；(b)光束质量随输出激光功率的变化曲线；(c)不同输出功率下的激光光谱；(d)最高输出功率时激光的时域和频域特性

Fig. 3 Output laser characteristics. (a) Output power and slope efficiency; (b) beam quality versus output laser power; (c) laser spectra under different powers; (d) time domain and frequency domain characteristics of laser at highest power

开展了输出激光功率的稳定性考核，4 kW 时连续输出 1830 s 的系统功率曲线如图 4 所示，功率最大波动为 2.5%。

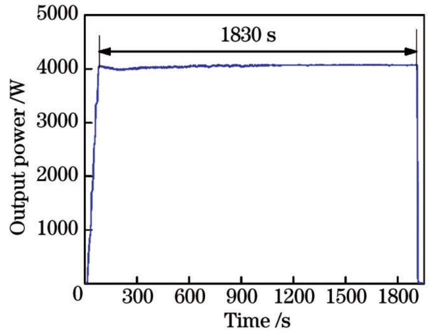

图 4　4 kW 功率输出稳定性考核结果

Fig. 4　Power output stability test result of laser system at 4 kW

自研 20 μm/400 μm 规格高品质掺镱双包层光纤的成功研制对于推进高功率光纤激光器中增益光纤的国产化具有重要意义。下一步，将优化系统设计、提高泵浦功率并对自研 20 μm/400 μm 规格光纤性能进行进一步研究。

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4 kW High-Beam-Quality Laser Output Using Homemade 20 μm/400 μm Yb-Doped Fiber

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Abstract

Objective　Fiber lasers are widely used in industry, national defense, and military fields owing to their advantages of high electro-optical efficiency, compact structure, and excellent stability, and Yb-doped fiber (YDF) lasers are a crucial fiber laser direction. Compared with 25 μm/400 μm fiber, 20 μm/400 μm YDF is less expensive and exhibits easier mode-controlling. Hence, 20 μm/400 μm YDF lasers have been widely applied and developed rapidly. Here, we successfully prepare high-quality 20 μm/400 μm YDF by improving the YDF preform fabrication technique. A master oscillator power amplifier (MOPA) system with the domestic 20 μm/400 μm double-clad YDF realizes the highest output laser power of 4 kW without the transverse mode instability (TMI) by adopting the backward pumping method.

Methods　Using a homemade 20 μm/400 μm double-clad YDF, we construct a MOPA system to test the property of the fiber at high power. The seed has a center wavelength of 1064 nm and output power of 19 W. A mode field adapter with a 10 μm/130 μm

input fiber and 20 μm/400 μm output fiber is adopted to connect the seed and the chirped and tilted fiber Bragg grating which is utilized to suppress the stimulated Raman scattering (SRS) signal. We adopt a cladding power stripper (CPS) before the main amplifier to discard the residual pump power from the backward pump sources. The active fiber of the amplifier is a 15-m-long 20 μm/400 μm YDF and coiled with a 9-cm diameter to suppress the TMI effect. The pump sources comprising five 976-nm-LD pump modules are injected into the 20 μm/400 μm YDF using a (6+1)×1 signal-pump combiner with a 25 μm/400 μm signal fiber. The maximum output power of each pump module is 1030 W. A CPS is utilized before the quartz block holder to discard the higher-mode in laser signal. After passing through the system, the output power of the seed decreases to 8 W. The beam quality of the output laser is measured at different output powers, and the TMI effect is assessed according to time-frequency characteristics. The continuous laser output power at the 4-kW level is recorded to examine the long term stability of the laser system.

Results and Discussions A laser output power of 4015 W with a slope efficiency of 81% is obtained . At the highest power, the beam quality factor (M^2) is approximately 1.39. The output laser spectrum has a center wavelength of 1064 nm and broadens as the output laser power increases. When the output power reaches 2875 W, the SRS effect emerges. The 3-dB linewidth of spectrum at the highest output power is 1.3 nm, and the Raman suppression ratio reaches 31 dB. Here, TMI does not emerge. In addition, the continuous stable operation at 4 kW is realized for 1830 s. The obtained result indicates that the maximum variation of output power is 2.5% (Fig. 4).

Conclusions Based on the homemade 20 μm/400 μm double-clad Yb-doped fiber, we construct a master oscillator power amplifier system to test the property of the fiber at high power. The output laser power reaches 4 kW with a center wavelength of 1064 nm and a slope efficiency of 81%. At the highest power, the M^2 is 1.39 and the Raman suppression ratio is better than 30 dB. In the future, we will optimize the structure of the laser system and increase the pump power to further study the property of homemade 20 μm/400 μm Yb-doped fiber.

Key words lasers; fiber lasers; high power; Yb-doped fibers; double-clad fibers