中国激光

同带泵浦的万瓦级三包层掺镱光纤

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摘要 同带泵浦是提升单纤输出能力的有效手段。在传统双包层光纤研究的基础上，为了进一步提高涂覆层的耐受性，本课题组制备了适用于同带泵浦的三包层大模场掺镱光纤，使大部分泵浦光束缚在含氟石英层内传输，大大减轻了泵浦光对低折射率涂层的冲击。基于所研制的三包层光纤搭建了全光纤化主控振荡功率放大器，实现了 9010 W 激光输出，激光中心波长为 1080 nm，斜率效率为 80.5%。三包层光纤的使用对万瓦级以上高功率激光光纤的长期可靠运行具有重要意义。

关键词 光纤光学；掺镱光纤；三包层光纤；同带泵浦；主振荡功率放大器

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高功率光纤激光器具有转换效率高、光束质量好、结构紧凑、免维护、易管理等优点，在工业加工、科研及国防等领域具有广泛应用[1-2]。提升稀土掺杂光纤的单纤输出能力一直是光纤激光器的研究热点。IPG 公司于 2009 年采用 1018 nm 同带泵浦方式，率先推出了 10 kW 单模光纤激光器[3]，并于 2013 年进一步将输出功率提升至 20 kW[4]。自 2017 年以来，国防科技大学、中国工程物理研究院和中国科学院上海光学精密机械研究所等国内研究单位先后采用 1018 nm 同带泵浦或 976 nm 激光二极管(LD)直接泵浦，基于大模场双包层光纤或泵浦增益一体化复合功能激光光纤，实现了高效率的单纤万瓦级激光输出[5-8]。

众所周知，在双包层光纤结构中，低折射率外包层以聚丙烯酸酯为主，其工作温度一般不超过 80 ℃。随着单纤输出功率的不断提升，高功率泵浦激光必将对低折射率涂层造成巨大压力，使之成为影响高功率掺镱双包层光纤工程化应用可靠性的重要因素。鉴于此，近年来，研究人员开始开展掺镱大模场三包层光纤的研制工作[9-10]，目前公开报道的三包层光纤的最大输出功率为 4.67 kW，其中增益光纤采用的是 Liekki 公司的 30/400/460 μm 三包层光纤[10]。三包层光纤(在双包层光纤的纯石英包层与低折射率涂覆层间加入低折射率的含氟石英玻璃层)可使绝大部分泵浦激光束缚在含氟石英玻璃层内传输，从而大大减轻高功率泵浦光对低折射率涂层的冲击。

此外，随着光纤放大功率的进一步提升，受限于 LD 的输出亮度，采用 LD 直接泵浦的方式已很难满足数万瓦量级的泵浦注入，采用高亮度的 1018 nm 同带泵浦方式[8]有效增加泵浦注入，减小量子亏损，降低光纤热负荷，是高功率光纤激光放大研究的重要趋势。然而，掺镱光纤对 1018 nm 泵浦光的吸收极低，不足 915 nm 的五分之一。常规的掺镱光纤需要较长的光纤才能实现有效的泵浦吸收，且在高功率条件下易引起非线性效应。因此，研制具有高吸收系数的掺镱三包层光纤成为克服上述两方面难题的关键。

最近，在双包层光纤研究的基础上，中国科学院上海光学精密机械研究所联合清华大学研究团队使

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用自主研发的适用于同带泵浦的 50/350/400 μm 三包层光纤，实现了 9010 W 激光输出，激光中心波长为 1080 nm，斜率效率为 80.5%。

采用改进的化学气相沉积法（MCVD）和溶胶-凝胶浸泡相结合的方式，制备了高镱离子浓度掺杂的 Al-P-Si 三元石英玻璃体系光纤预制棒。将该预制棒包层的截面加工成八边形，套上数值孔径 *NA* 相对纯石英约为 0.22 的含氟石英管，获得了三包层光纤预制棒；随后进行拉丝、涂覆获得了尺寸为 50/350/400 μm 的三包层光纤。光纤的折射率（*n*）分布如图 1 所示。光纤的主要性能参数指标如下：纤芯 *NA* 约为 0.06，吸收系数约为 0.6 dB/m@1018 nm，包层 *NA* 约为 0.22，光纤截面为正八边形，外包层 *NA* 约为 0.46。

采用溶胶-凝胶浸泡方法可以显著提高稀土离子的溶解度，减少镱离子团簇，实现光暗化抑制的同时提高光纤在 1018 nm处的吸收系数。该三包层光纤及普通 20/400 μm 双包层光纤的纤芯元素分布（EPMA）如图 2 所示。可以看到，三包层光纤纤芯中镱离子的掺杂浓度明显高于普通 20/400 μm 光纤。在提高纤芯镱掺杂浓度的同时，为了不使纤芯折射率偏高，增加了纤芯的含氟量。

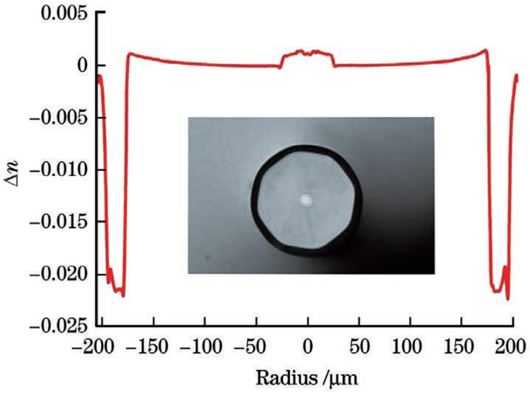

图 1　光纤端面和折射率分布

Fig. 1　Fiber cross section and its refractive index

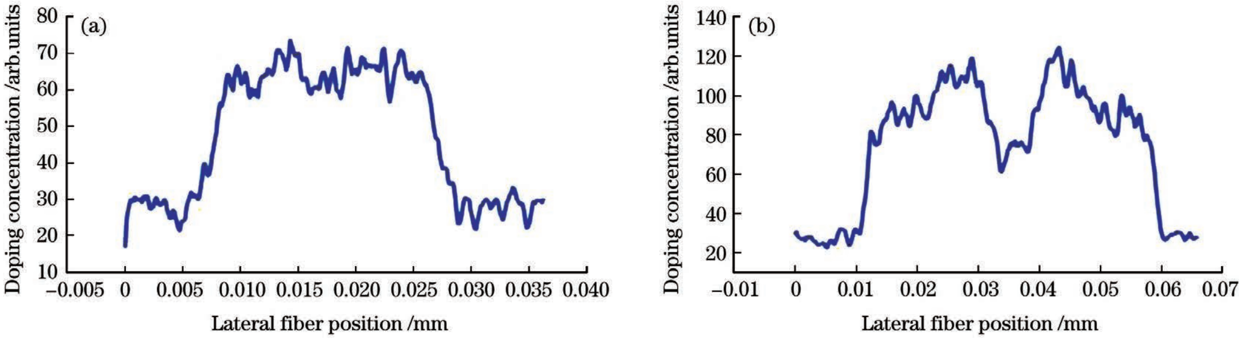

图 2　镱掺杂浓度。(a)普通 20/400 μm 光纤；(b)三包层光纤

Fig. 2　Yb-doped concentration. (a) Normal 20/400 μm fiber; (b) triple-clad fiber

研制的高吸收系数掺镱三包层光纤由清华大学高功率光纤激光团队开展了初步的放大测试。光纤激光测试系统采用全光纤化单模种子激光加一级放大主控振荡器的功率放大器，如图 3 所示。种子激光功率为 600 W，放大级采用 1018 nm 同带抽运结构，在放大级吸收的抽运光功率达到 11606 W 时激光输出功率可达到 9010 W，中心波长为 1080 nm，斜率效率为 80.5%，如图 4 所示。这是目前国内首个基于 1018 nm 同带泵浦的单纤近万瓦三包层光纤。阻止光纤功率进一步提升的原因在于三包层有源光纤第二内包层为圆形，而激光器系统其他部分的无源纤是内包层尺寸为 395 μm的双包层光纤。

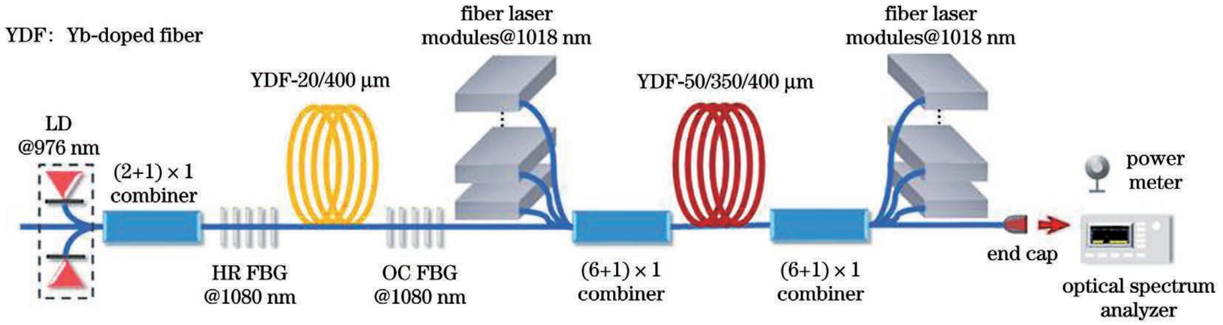

图 3　光纤激光测试系统结构图

Fig. 3　Fiber laser experimental setup for fiber characterization

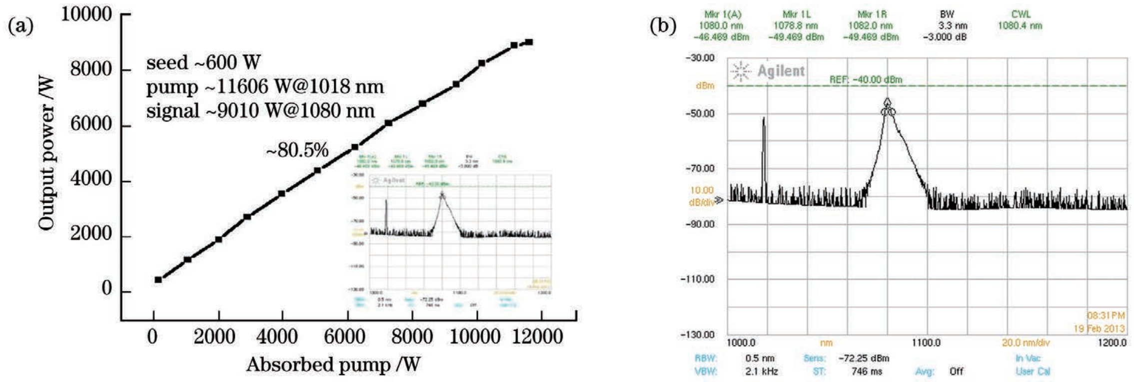

图 4　激光输出功率曲线及光谱图。(a)输出功率;(b)光谱图

Fig. 4　Laser output power and spectrum. (a) Output power; (b) spectrum

这使得部分注入的 1018 nm 泵浦光耦合进入三包层光纤的圆形含氟石英包层形成螺旋光而无法被吸收,故在最终的高功率激光实验中,仅开启前向泵浦。通过光谱积分计算可得残余泵浦功率约占输出功率的 7.7%,即约 751 W;采用 1018 nm 同带泵浦以最大激光功率输出时,注入的泵浦光总功率为 12357 W,光纤的泵浦吸收效率为 12.15 dB。下一步,本研究团队将改进光纤和放大器激光系统的设计,减少耦合进入含氟石英包层的泵浦光,进一步提升光纤的激光输出能力。

采用自主研发的 50/350/400 μm 大模场三包层增益光纤,在同带泵浦条件下实现了 9010 W 功率的激光输出,这是我国高功率光纤激光材料研究领域的重要进步。该光纤采用三包层光纤结构设计,可大大缓解高功率激光运行条件下泵浦光对传统双包层光纤低折射率涂覆层的冲击,对于高功率激光光纤的长期可靠运行具有重要意义。

参　考　文　献

[1] Richardson D J, Nilsson J, Clarkson W A. High power fiber lasers: current status and future perspectives[J]. Journal of the Optical Society of America B, 2010, 27(11): B63-B92.

[2] Zervas M N, Codemard C A. High power fiber lasers: a review[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2014, 20(5): 219-241.

[3] Stiles E. New developments in IPG fiber laser technology[C]//Proceedings of the 5th International Workshop on Fiber Lasers, September 30-October 1, Dresden, Germany. New York: ACM, 2009: 1-2.

[4] Shiner B. The impact of fiber laser technology on the world wide material processing market[C]//CLEO: Science and Innovations 2013, June 9-14, 2013, San Jose, California United States. Washington, D. C.: OSA, 2013: AF2J.1.

[5] Lin A X, Zhan H, Peng K, et al. 10 kW-level pump-gain integrated functional laser fiber[J]. High Power Laser and Particle Beams, 2018, 30(6): 060101.
林傲祥, 湛欢, 彭昆, 等. 国产复合功能光纤实现万瓦激光输出[J]. 强激光与粒子束, 2018, 30(6): 060101.

[6] Lin H H, Tang X, Li C Y, et al. The localization single-fiber laser system obtained 10.6 kW laser output[J]. Chinese Journal of Lasers, 2018, 45(3): 0315001.
林宏奂, 唐选, 李成钰, 等. 全国产单纤激光系统获得 10.6 kW 激光输出[J]. 中国激光, 2018, 45(3): 0315001.

[7] Chen X L, Lou F G, He Y, et al. Home-made 10 kW fiber laser with high efficiency[J]. Acta Optica Sinica, 2019, 39(3): 0336001.
陈晓龙, 楼风光, 何宇, 等. 高效率全国产化 10 kW 光纤激光器[J]. 光学学报, 2019, 39(3): 0336001.

[8] Gao C, Dai J Y, Li F Y, et al. Homemade 10-kW ytterbium-doped aluminophosphosilicate fiber for tandem pumping[J]. Chinese Journal of Lasers, 2020, 47(3): 0315001.
高聪, 代江云, 李峰云, 等. 自研万瓦级同带泵浦掺镱石英玻璃光纤[J]. 中国激光, 2020, 47(3): 0315001.

[9] Liu S, Zhan H, Peng K, et al. Yb-doped aluminophosphosilicate triple-clad laser fiber with high efficiency and excellent laser stability[J]. IEEE Photonics Journal, 2019, 11(2): 1501010.

[10] Kalyoncu S K, Mete B, Yeniay A. Diode-pumped triple-clad fiber MOPA with an output power scaling up to 4.67 kW[J]. Optics Letters, 2020, 45(7): 1870-1873.

Yb-Doped Triple-Clad Fiber for Nearly 10 kW Level Tandem-Pumped Output

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Abstract

Objective Since the development of Yb-doped fiber laser, increasing the output of a single fiber has been one of the most important directions. The output of a single fiber has now been able to attain 10 kW-level or above. However, these results are mainly laboratory reports, and few fibers have been adopted in practical applications because the coating material of these double cladding fibers age quickly due to the injected high pump power and large amount of quantum defect heating. To minimize the impact of high pump power on coating materials, triple-clad Yb-doped fibers, with an addition of fluorine-doped fused silica between silica and low-index coating, have been suggested. For a given fiber, high brightness of the tandem-pumping can not only reduce the quantum defect heating, but also further increase the pump injection and output-power scaling. To achieve a more reliable and higher laser output, a highly Yb-doped triple-clad fiber used for tandem-pumping is proposed.

Methods The Yb-doped fiber preform has been prepared by modified chemical vapor deposition (MCVD) in combination with sol-gel solution-doping method to improve the Yb-doped concentration without clusters. The doped preform was overcladded and shaped via grinding in an octagonal shape to form the pump cladding. The preform was further surrounded by the second highly fluorine-doped synthetic fused silica cladding with a depressed refractive index to form the out cladding. Then, the preform was drawn and coated as conventional double cladding fiber to obtain the triple-clad fiber (Fig. 1). The fiber was characterized by refractive index profiling, electron probe microanalysis (EPMA), loss, and absorption. Finally, the fiber laser performance was characterized.

Results and Discussions The fiber is 50/350/400 μm core-clad diameter, 0.06/0.22/0.46 *NA*, and approximately 0.6 dB/m inner cladding absorption at 1018 nm. The EPMA results showed that the homemade triple-clad fiber has a much higher Yb-doped concentration than the commonly used 20/400 μm double cladding fiber (Fig. 2). The reduced core numerical aperture was achieved by higher fluorine-doped silica, and laser performance of the fiber was demonstrated by an all-fiber master oscillator power amplifier at 1080 nm. Figure 3 shows the experimental setup; the seed laser is about 600 W, generated via a 20/400 μm Yb fiber laser oscillator. The triple-clad fiber was used as a gain medium in the power amplifying stage, and the pump sources are 1018 nm fiber lasers. When about 11606 W pump power was absorbed, up to 9010 W laser output with a slope efficiency of 80.5% was achieved (Fig. 4). Further power scaling was limited by the unabsorbed helical light in the fluorine-doped fused silica cladding, which is round-shaped. Thus, in the high-power laser experiment, only the forward pump was on. In future studies, we will improve the design of fiber laser setup and reduce the pump power in the fluorine-doped silica to further increase the fiber laser output.

Conclusions A maximum 9010 W laser output was achieved by the 1018 nm tandem-pumping using the homemade 50/350/400 μm large-mode-area Yb-doped triple-clad fiber. This is an important progress in the field of high-power fiber laser materials. Compared with double cladding fiber, the triple-clad fiber design, which deliveries most of the pump light inside the fluorine-doped fused silica, can greatly minimize the aging effect of the pump light on the coating material. This is of great significance for the long-term operation reliability of high-power laser fiber.

Key words fiber optics; Yb-doped fiber; triple-clad fiber; tandem-pumping; master oscillator power-amplifier

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