快报

国产双锥形光纤实现 4 kW 单模激光输出

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摘要 基于自主研制的双锥形掺镱双包层光纤，开展了全光纤高功率光纤激光放大实验。激光系统实现了中心波长为 1080 nm、最高功率为 4 kW 的单模激光输出，其光光效率和斜率效率分别为 82% 和 83%，质量因子(M^2)为 1.33，拉曼抑制比为 44 dB。实验结果表明，双锥形光纤具有同时提高非线性效应和模式不稳定性效应阈值的优势，有利于进一步提升高光束质量光纤激光器的输出功率。

关键词 激光器；高功率光纤激光器；锥形光纤；单模；受激拉曼散射；模式不稳定

中图分类号 TN248 **文献标志码** A **doi**：10.3788/CJL202148.0115002

近年来，我国针对高光束质量、高功率光纤激光器方面的研究取得了长足进步[1-3]，高光束质量、高功率光纤激光器在工业领域的应用也越来越广泛。目前，高光束质量光纤激光器的输出功率的进一步提升主要受限于受激拉曼散射和受激布里渊散射等非线性效应以及模式不稳定性效应[4]。增加大模场增益光纤的纤芯直径有利于抑制非线性效应，但这可能会导致光束质量的退化。与常规的均匀直径光纤相比，锥形光纤的纤芯直径随长度的增加逐渐增加，具有抑制非线性效应的先天优势，且满足绝热拉锥条件的锥区有利于实现良好的光束质量[5]。2008 年，芬兰坦佩雷理工大学首次以锥形掺镱光纤作为增益介质，通过空间结构实现了 84 W 的连续宽谱激光输出[6]，光束质量因子 M^2 为 1.07。2010 年，该单位将输出功率提升至 750 W，M^2 为 1.7[7]。之后，俄罗斯科学院、加拿大国家光学研究所、国防科技大学等多家单位对基于锥形掺镱双包层光纤的高功率/高能量光纤激光器展开深入研究，将其应用于窄线宽激光放大[8]、单频激光放大[9-11]、脉冲激光输出[12-15]等多个方面。2020 年，国防科技大学进一步提出了“纺锤形”结构的双锥形掺镱双包层光纤[16]（下文简称为“双锥形光纤”）。该类型光纤具有两端小、中间大和芯包比保持不变的特点。在双锥形光纤中，当纤芯中的信号光在由粗到细的锥形缓变区传输时，纤芯中的高阶模将逐渐被滤除到内包层，因此模式不稳定性效应的阈值有望得到进一步的提高。最近，国防科技大学基于自主研制的双锥形光纤搭建了全光纤结构的主振荡功率放大器，采用双端抽运的方式实现了 4 kW 的单模激光输出，最高功率时的 M^2 为 1.33。

该光纤的横截面如图 1(a)所示，光纤两端的纤芯、包层直径分别为 22 μm 和 413 μm（常表示为 22/413 μm），光纤中间均匀区的纤芯、包层直径为 32/600 μm（纤芯直径根据包层直径估算）。图 1(b)给出了该光纤包层直径随光纤长度的变化情况，可以看到双锥形光纤的总长度约为 21 m，其中两端均匀区的光纤长度约为 1 m，中间均匀区长度约为 10 m，两端锥形缓变区长度分别为 4 m 和 5 m。光纤纤芯数值孔径 NA 约为 0.06。实验中，光纤盘绕半径约为 5～10 cm。

图 2 为基于双锥形光纤搭建的主振荡功率放大器的实验系统结构图。种子源的中心波长为 1080 nm，输出功率为 103 W。种子光经模场适配器(MFA)和包层光滤除器(CLS)后进入放大级。这里采用双端抽运的方式进行激光放大，抽运源为 7 组中心波长为 976 nm 的 LD，每组抽运功率最高约为 800 W，其中 2 组 LD 用于前向抽运，5 组 LD 用于后向抽运。为了进一步提高系统的效率且保证良

收稿日期：2020-09-10；**修回日期**：2020-09-26；**录用日期**：2020-10-10
基金项目：湖南创新型省份建设专项(2019RS3018)、湖南省自然科学基金创新研究群体项目(2019JJ10005)
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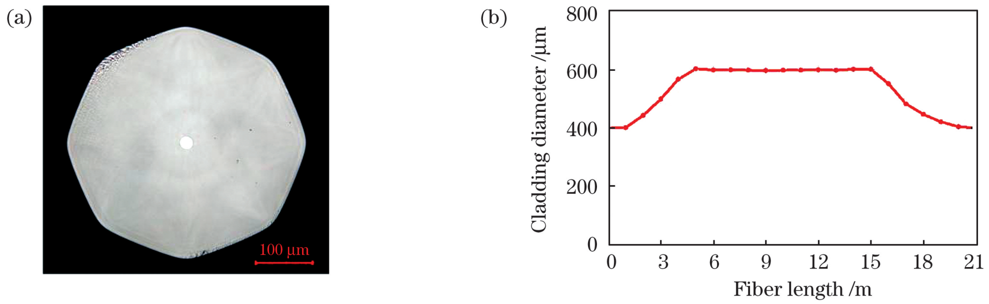

图 1　自研双锥形光纤参数。(a)光纤横截面的显微镜图片;(b)光纤包层直径随光纤长度的变化

Fig. 1　Parameters of home-made double tapered active fiber. (a) Microscopic image of fiber cross section; (b) cladding diameter varying with fiber length

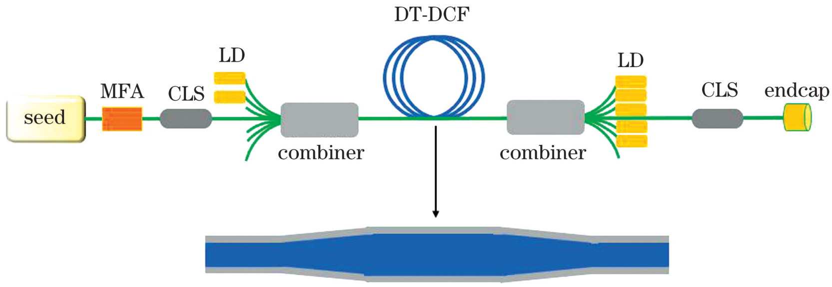

图 2　基于双锥形光纤搭建的主振荡功率放大器的实验装置图

Fig. 2　Experimental setup of master oscillator power amplifier based on double-tapered fiber

好的光束质量,前向合束器和后向合束器的信号臂光纤规格分别为 20/400 μm 和 25/400 μm。放大后的激光经 CLS 后通过端帽被输出至自由空间,用于功率、光谱和光束质量等参数的测量。

图 3(a)给出了主放大级输出功率和光束质量随抽运功率的变化情况。可以看出,输出功率随抽运功率呈线性增加,在抽运功率为 4.75 kW(前向抽运功率和后向抽运功率分别为 1.31 kW 和 3.44 kW)时,输出功率达到 4 kW,对应的光光效率和斜率效率分别达 82%和 83%,此时 M^2 为 1.33。在不同的抽运功率下,M^2 保持在 1.3 左右。双锥形光纤中间均匀区和锥形缓变区总长可达 19 m,且这两部分光纤的纤芯较粗。因此,在前述弯曲条件下,基于弯曲损耗的高阶模抑制效应作用较弱。系统的单模输出主要得益于双锥形光纤中输入端锥形缓变区的基模保持能力和输出端锥形缓变区对高阶模的抑制能力。当进一步增加抽运功率时,可以探测到输出光的时域出现 kHz 量级的波动,这意味着

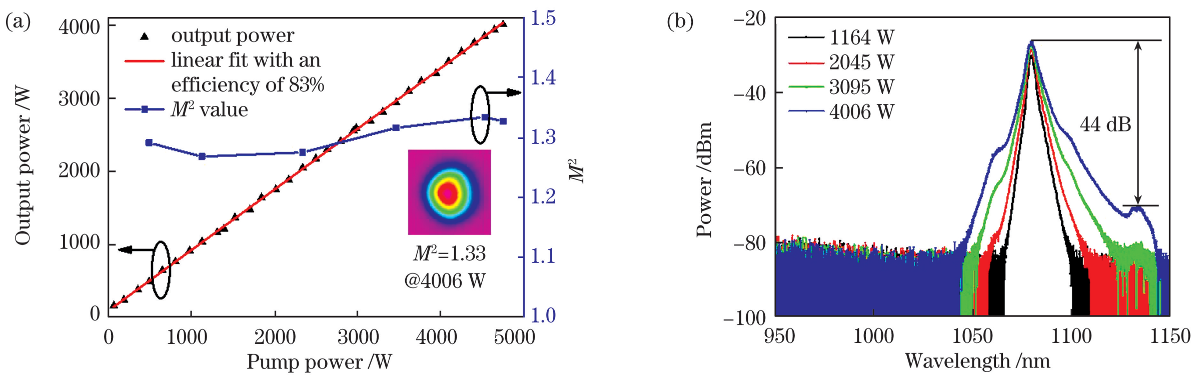

图 3　输出功率及光束质量随抽运功率的变化以及不同输出功率下的激光光谱。(a)输出功率及光束质量随抽运功率的变化;(b)不同输出功率下的激光光谱

Fig. 3　Output power and beam quality varying with pump power, and spectra under different output powers. (a) Output power and beam quality varying with pump power; (b) spectra under different output powers

模式不稳定效应的出现。此时，还观察到斜率效率明显下降，因此，本实验未继续增加抽运功率。图 3(b)给出了不同输出功率下的光谱，可以看到输出光束几乎无残余的抽运光，输出激光的中心波长为 1080 nm，其光谱随着输出功率的增大明显展宽。当输出功率为 3095 W 时，可观察到微弱的一阶拉曼光成分。在最高功率下，信号光的 3 dB 带宽约为 3.9 nm，光谱中拉曼光强度较信号光低约 44 dB。由此可见，双锥形光纤使得增益光纤的模场面积整体上大幅提升，对非线性效应的抑制作用明显。

本文所实现的基于双锥形光纤的 4 kW 单模激光输出对于推动国产化高品质激光光纤关键技术自主可控具有重要意义。下一步工作将从双锥形光纤结构优化设计、抽运方式优化等方面继续提高模式不稳定效应的阈值，以获得更高功率的单模激光输出。

致谢　感谢张嵩、肖亮、何加威等在实验系统搭建和测试中给予的支持和帮助。

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4-kW Single-Mode Laser Output Using Homemade Double-Tapered Fiber

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Abstract

Objective In recent years, there has been a rapid progress in the development of high-power fiber lasers, which are widely used in the fields of laser marking and material processing as well as numerous industrial applications. The main factors that limit the output power of fiber lasers are the mode instability and nonlinear effects, including stimulated Raman scattering and stimulated Brillouin scattering. To suppress these nonlinearities, the core size of large mode area active fibers should be increased. However, this may lead to the degradation of beam quality. The core diameter of tapered fibers gradually increases as the length increases, therefore suppressing the nonlinear effects. Moreover, the tapered area, which satisfies the adiabatic taper principle, facilitates in achieving excellent beam quality. Tapered active fibers have been used in various applications such as continuous-wave fiber laser oscillators or amplifiers, ultrafast laser systems, and single-frequency fiber amplifiers. In early 2020, researchers from National University of Defense Technology proposed the Yb-doped double-tapered double-cladding fiber (DT-DCF), which consists of a thin-core section at both ends and a large-core section in the middle. In the present study, all-fiber high-power laser amplification is performed based on the self-fabricated Yb-doped DT-DCF. The laser system achieves a single-mode laser output with a maximum power of 4 kW and a mass factor M^2 of 1.33.

Methods We construct a master oscillator power amplifier system based on the homemade DT-DCF. This system is 21-m long and has small-core and large-core sections with core/cladding diameters of 22/413 and 32/600 mm, respectively. Fusion splices connect all the components. The seed has a center wavelength of 1080 nm and a output power of 103 W. After passing through the cladding light striper (CLS), the seed light is injected into the amplifier. Subsequently, bidirectional pumping is applied to laser amplification. Seven laser diode (LD) modules with a center wavelength of 976 nm are divided into two groups comprising two and five modules to pump the DT-DCF through the forward and backward couplers, respectively. After the amplification stage, the CLS is utilized to strip out the residual pump power and the laser is finally output to free space through the endcap for the measurement of power, spectrum, and beam quality.

Results and Discussion The output power increases linearly with the pumping power. When the pumping power is 4.75 kW, the output power reaches 4 kW. The corresponding optical efficiency and slope efficiency are 82% and 83%, respectively. The M^2 at the highest power is 1.33 [Fig. 3(a)], exhibiting the single-mode output characteristic of the system. Mode instability limits further power scaling of the single-mode output. If the pump power increases to over 4.75 kW, time domain fluctuation of kHz can be observed, indicating the initiation of mode instability. The output laser has a center wavelength of 1080 nm, and its spectrum broadens as the output power increases. For the spectrum under the highest output power, the Raman suppression ratio reaches up to 44 dB [Fig. 3(b)], demonstrating the ability of the DT-DCF to inhibit the nonlinear effects.

Conclusions In summary, we have established a 1080-nm all-fiber amplifier based on DT-DCF. This amplifier can achieve a 4-kW single-mode output laser with a slope efficiency of 83% and M^2 of 1.33. Our results indicate that the DT-DCF can simultaneously suppress the nonlinear effects and transverse mode instability, thus providing a beneficial reference for further power scaling of single-mode fiber lasers.

Key words lasers; high-power fiber laser; tapered fiber; single mode; stimulated Raman scattering; mode instability

OCIS codes 140.3510; 140.3570; 140.3615; 190.4370